Determining of optimum irrigation schedules for drip irrigated Shiraz vineyards in the Breede River Valley

by

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Declaration

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SUMMARY

Shiraz/110R grapevines, growing in a fine sandy loam soil in the Breede River Valley, were subjected to ten different drip irrigation strategies during the 2006/07, 2007/08 and 2008/09 seasons. Grapevines of the control treatment (T1) were irrigated at 30% to 40% plant available water (PAW) depletion throughout the growing season. Grapevines of three treatments were irrigated at 70% to 80% PAW depletion from bud break until véraison (*i.e.* when *ca.* 95% of grape berries have changed colour), followed by either irrigation at 30% to 40% PAW depletion (T2) or a continuous deficit irrigation (CDI) strategy (T3) or irrigation at 70% to 80% PAW depletion (T4) during ripening. The CDI strategy was obtained by applying *ca.* half the volume of water that was applied to the control. This allowed the soil to dry out gradually between physiological stages (*i.e.* bud break and véraison or véraison and harvest). Grapevines of three further treatments were irrigated at *ca.* 90% PAW depletion from bud break until véraison, followed by irrigation at 30% to 40% PAW depletion (T5) or a CDI strategy (T6) or irrigation at *ca.* 90% PAW depletion (T7) during ripening. Grapevines of two treatments were irrigated by means of a CDI strategy from bud break until véraison. For both treatments, the soil water content (SWC) was allowed to dry out gradually until *ca.* 90% PAW depletion was reached. After véraison, the SWC of the one treatment was maintained at *ca.* 90% PAW depletion by applying only four small irrigations of three hours each during ripening (T8). The soil of the other treatment, received an irrigation at véraison to refill the SWC to field capacity (T9) followed by the CDI strategy during ripening. Grapevines of the tenth treatment were irrigated at *ca.* 90% PAW depletion between bud break and véraison followed by a partial profile refill (PPR) strategy during ripening (T10). In order to obtain the PPR strategy, SWC was only maintained between 40% and 60% PAW depletion.

Evapotranspiration varied between 3.5 mm/day and 0.1 mm/day for driest and wettest treatments, respectively, during the period between December and February. This was substantially less than the volumes required for full surface irrigation. For irrigations applied at 30% to 40% PAW depletion (T1), 70% to 80% PAW depletion (T4) and *ca.* 90% PAW depletion (T7) levels throughout the season, crop coefficients for the Penman-Monteith reference evapotranspiration (ET_o) were 0.4, 0.2 and 0.1, respectively.

Under the given conditions, the different irrigation strategies did not have any effect on root distribution and density. Shoot growth of grapevines exposed to high to severe water deficits in the pre-véraison period stopped before mid December. Shoots of grapevines that were exposed to high or severe water deficits before véraison followed by more frequent irrigation during ripening showed active re-growth. These trends occurred during all the seasons.

The level of PAW depletion reflected strongly in the plant water potential in the grapevines. Leaf water potential was influenced by the prevailing atmospheric conditions, whereas stem water potential was less sensitive to atmospheric conditions, but responded more directly to soil water availability. Due to the good relationships between pre-dawn leaf, mid-day leaf, mid-day stem and total diurnal water potential, it was possible to re-classify the water status in terms of previous classifications for these water potentials based on pre-dawn measurements. Water constraints in T1, T2 and T5 grapevines were classed as experiencing no stress, whereas the T7 and T8 ones experienced strong to severe water constraints before harvest.

High frequency irrigation strategies during ripening delayed sugar accumulation due to dilution of sugar in the larger berries. Except for the wettest strategy, and where grapevines were subjected to the CDI strategy throughout the season, berry mass increased during ripening, *i.e.* from véraison to harvest. Water deficits had a negative effect on berry mass, bunch size and yield. Where higher soil water depletion levels were allowed, irrigation strategies had a positive effect on the irrigation water productivity of grapevines compared to the frequently irrigated or CDI strategies.

Higher water constraints in grapevines, particularly during ripening, improved sensorial wine colour and enhanced some of the more prominent wine aromas, *e.g.* spicy and berry. Grapevines that were irrigated at a high frequency during ripening produced wines with diluted character flavours and aromas and inferior overall quality. Under the given conditions, sensorial wine colour and spicy character were the dominant factors in determining overall sensorial wine quality.

OPSOMMING

Shiraz/110R wingerdstokke in 'n fyn sandleem grond in die Breede Rivier vallei is gedurende die 2006/07, 2007/08 en 2008/09 seisoene met tien verskillende drupbesproeiingstrategieë besproei. Wingerdstokke van die kontrole (B1) is deur die seisoen by 30% to 40% plant beskikbare water (PBW) onttrekking besproei. Drie behandelings is tussen bot en deurslaan (wanneer *ca.* 95% van die korrels verkleur het) by 70% tot 80% PBW onttrekking besproei, gevolg deur besproeiing by 30% tot 40% PBW onttrekking (B2), 'n deurlopende tekort besproeiing (DTB) strategie (B3) of besproeiing by 70% tot 80% PBW onttrekking (B4) gedurende rypwording. In die geval van die DTB strategie is ongeveer die helfte van die volume water toegedien wat by die kontrole toegedien is. Laasgenoemde strategie het die grond toegelaat om geleidelik tussen fisiologiese fases (*i.e.* tussen bot en deurslaan of tussen deurslaan en oes) uit te droog. Drie ander behandelings is by *ca.* 90% PBW onttrekking tussen bot en deurslaan besproei, gevolg deur besproeiing by 30% tot 40% PBW onttrekking (B5) of 'n DTB strategie (B6) of besproeiing by *ca.* 90% PBW onttrekking (B7) gedurende rypwording. Wingerdstokke van twee ander behandelings is d.m.v. 'n DTB strategie vanaf bot tot deurslaan besproei. Beide behandelings se grondwaterinhoud (GWI) was toegelaat om geleidelik uit te droog tot *ca.* 90% PBW onttrekking bereik was. Na deurslaan was die GWI van die een behandeling naby *ca.* 90% PBW onttrekking gehandhaaf deur slegs vier klein besproeiings van drie uur elk gedurende rypwording toe te pas (B8). Die grond van die ander behandeling het tydens deurslaan 'n besproeiing ontvang om die GWI tot by veldkapasiteit te hervul (B9) en is tydens rypwording weer d.m.v. 'n DTB strategie besproei. Stokke van die tiende behandeling is tussen bot en deurslaan by *ca.* 90% PBW onttrekking besproei, gevolg deur besproeiing d.m.v. 'n gedeeltelike profiel hervul (GPH) strategie tydens rypwording (B10). Om 'n GPH strategie toe te kon pas, is tussen 40% en 60% PBW ontrekking gehandhaaf.

Evapotranspirasie het tussen 3.5 mm/dag en 0.1 mm/dag vir onderskeidelik die natste en droogste behandelings tussen Desember en Februarie gevarieer. Dit was aansienlik laer as volumes wat vir voloppervlak besproeide wingerde benodig word. In die geval van besproeiing by 30% tot 40% PBW onttrekking (B1), 70% tot 80% PBW onttrekking (B4) en *ca*. 90% PBW onttrekking (B7) deur die loop van die seisoen

was die gewasfaktore vir die verwysingverdamping (ET_o) 0.4, 0.2 en 0.1 onderskeidelik.

Onder die gegewe toestande het die verskillende besproeiingstrategieë geen effek op die worteldigtheid en –verspreiding gehad nie. Lootgroei van wingerdstokke wat aan hoë tot baie hoë watertekorte blootgestel was voor deurslaan, het voor middel Desember gestop. Lote van wingerdstokke wat aan hoë tot baie hoë watertekorte voor deurslaan blootgestel is, gevolg deur besproeiing teen ’n hoë frekwensie tydens rypwording, het aktiewe hergroei getoon.

Die PBW ontrekkingspeil het sterk in die plantwaterpotensiale van wingerdstokke weerspieël. Blaarwaterpotensiaal is deur heersende klimaatstoestande beïnvloed, terwyl stamwaterpotensiaal minder sensitief teenoor die klimaat was, maar meer direk deur die beskikbaarheid van grondwater beïnvloed is. Vanweë die goeie verband tussen voordagbreek blaar-, mid-dag blaar-, mid-dag stam- en totale daaglikse waterpotensiaal, was dit moontlik om water status van die stokke te her-klassifiseer in terme van vorige vir waterpotensiaalklassifikasies wat op voordagbreek waardes gebasseer is. Waterspanning in B1, B2 en B5 stokke is as geen spanning geklassifiseer, terwyl dié van B7 en B8 voor oes in die hoë tot baie hoë klasse geval het.

Hoë frekwensie besproeiing strategieë gedurende rypwording kan suikertoename a.g.v. die groter korrels vertraag. Met die uitsondering van die natste strategie, asook waar stokke volgens die DTB strategie deur die seisoen besproei is, het korrelmassa gedurende rypwording toegeneem. Watertekorte het ’n negatiewe effek op korrelmassa, trosgrootte en produksie gehad. Besproeiingstrategieë waar ’n hoë mate van grondwateronttrekking voor besproeiings toegelaat is, het ’n positiewe effek op die besproeiingwaterproduktiwiteit van wingerd in vergelyking met gereelde besproeiings of ‘n DTB strategie gehad.

Watertekorte, veral gedurende rypwording, het ’n verbetering in sensoriese wynkleur en meer prominente wyn aromas, tot gevolg gehad. Besproeiing teen hoë frekwensies gedurende rypwording, het wyne met ’n afgewaterde smaak en aroma karakters asook ’n swak algehele gehalte produseer. Sensoriese wynkleur en spesery karakter die dominante faktore in die bepaling van algehele kwaliteit.

This thesis is dedicated to Candice, my parents, brothers and family.

"Grapes are the most noble and challenging of fruits."

Malcolm Dunn, Head gardener of the 7th Viscount Powerscourt

BIOGRAPHICAL SKETCH

Eugene Lourens Lategan (Vink) was born on 18 October 1978 in Johannesburg. He started his school career at Gene Louw Primary School near Cape Town. He continued his schooling in Rundu (Namibia) and Port Elizabeth before returning to Cape Town where he matriculated at President High School in 1996. In 1998 he enrolled at the Stellenbosch University and in 2003, he started working at Cape Irrigation Consultants as an irrigation consultant, working primarily on grapevines. He obtained a BScAgric degree in 2005 at the Stellenbosch University, majoring in Soil Science and Viticulture. In 2006 he obtained his BScAgricHons (Soil Science) degree. Since November 2005 until present, he is a junior researcher at the Infruitec-Nietvoorbij Institute for Fruit and Wine of the Agricultural Research Council.

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PREFACE

This thesis is presented as a compilation of five chapters. Each chapter is introduced separately and is written according to the style of the South African Journal of Enology and Viticulture.

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Chapter 3	**Research results** The effect of different irrigation strategies on the evapotraspiration and crop coefficients for Shiraz in the Breede River Valley region
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MEANING	ABBREVIATION/UNIT
abscisic acid	ABA
Agricultural Research Council	ARC
analysis of variance	ANOVA
and others (*et alii*)	*et al.*
approximately (*circa*)	*ca.*
before Christ	BC
carbon	C
centimetre	cm
centimole charge per kg	cmol(+)/kg
continuous deficit irrigation	CDI
copper sulfide	$CuSO_4$
crop coefficient	K_c
cubic metre	m^3
cubic metre per hectare	m^3/ha
cultivar	cv.
deciSiemens per metre	dS/m
degrees	º
degrees Balling	ºB
degrees Celsius	ºC
density of water	ρ_w
diameter	Ø
diammonium phosphate	DAP
electrical conductivity of saturated soil extract	EC_e
equation	eq.
evapotranspiration	ET_c
field water capacity	FC
figure	Fig.
for example (*exampli gratia*)	*e.g.*
fresh weight	FW
gram	g
gram per berry	g/berry
gram per hectolitre	g/hL
gram per litre	g/L
gravimetric soil water content	P_W
growing degree days	GDD
irrigation water production	IWP
irrigation water use index	IWUI
least significant difference	LSD
phosphorus	P
potassium	K
potassium nitrate	KNO_3
kilometre	km
kilogram	kg
kilogram per hectare	kg/Ha

kilogram per cubic metre	kg/m^3
kilopascal per degree Celsius	kPa/ºC
leaf water potential (mid-day)	Ψ_L
litre per hour	L/h
manganese	Mg
mega joules per square metre per day	$MJ/m^2/day$
mega joules per square metre per hour	$MJ/m^2/h$
megapascal	MPa
metre per second	m/s
milligram per kilogram	mg/kg
milligram per litre	mg/L
millimetre	mm
millimetre per day	mm/day
millimetre per millimetre	mm/mm
nanometre	µm
negative logarithm of the molar concentration of dissolved hydrogen ions	pH
net solar radiation	R_n
nitrogen	N
overall sensorial wine quality	Q_w
partial profile refill	PPR
percentage	%
permanent wilting point	PWP
plant available water	PAW
pre-dawn leaf water potential	Ψ_{PD}
reference evapotranspiration	ET_o
relative humidity	RH
sensorial wine colour	C_w
sensorial wine spicy character	S_w
sodium	Na
soil water content	SWC
soil water matric potential	Ψ_M
soil bulk density	ρ_b
South African Wine Industry Information and Systems	SAWIS
standard error	s.e.
square metre	m^2
stem water potential (mid-day)	Ψ_S
sulphur dioxide	SO_2
temperature	T
that is (id est)	*i.e.*
ton per hectare	t/ha
ton per megaliter	t/ML
total titratable acidity	TTA
total diurnal leaf water potential	Ψ_T
total soluble solids	TSS
vapour pressure deficit	VPD
volumetric soil water content	θ_v

Chapter 1

GENERAL INTRODUCTION AND PROJECT AIMS

CHAPTER 1
GENERAL INTRODUCTION AND PROJECT AIMS

1.1 INTRODUCTION

South Africa is a relatively dry country with a mean annual rainfall of 450 mm and a high evaporation rate (NWRS, 2004). Only 7% of the country's area receives more than the mean annual world rainfall of 860 mm (NWRS, 2004). The mean annual rainfall is the lowest in the north-eastern part of South Africa and gradually increases to the east south-eastern part of the country (Fig. 1.1). The Western Cape, where 95% of the 101 325 hectares total wine grape vineyards in the South African wine industry are planted, has a mean annual rainfall of 348 mm which is quite erratically distributed due to the high mountain ranges in the province (Cupido & Isaacs, 2009; NWRS, 2004).

In 2008, approximately 53% of the vineyards were being irrigated and/or established under drip irrigation compared to less than 23% in 1996 (Cupido & Isaacs, 2009). Water savings obtained by using drip irrigation are in line with the optimal use of water resources as prescribed by the South African National Water Act no. 36 of 1998. Since the root volumes of grapevines established under drip irrigation are generally limited, water deficits can occur, or applied, more readily compared to full surface irrigation, *e.g.* micro-sprinklers. Hence, it is necessary to establish the positive or negative effects of water constraints on the yield components and wine quality characteristics of grapevines during different physiological stages. This knowledge will enable farmers and growers to schedule irrigation and manage limited and expensive resources, *i.e.* water and electricity, to limit water deficits in critical periods or create such deficits to obtain the best possible wine quality.

Most of the irrigation research in South Africa on wine grapes was carried out in flood or micro-sprinkler irrigated vineyards (Van Zyl, 1984; Myburgh, 2005; Myburgh, 2006; Myburgh, 2007; Myburgh, 2011). Consequently, knowledge regarding the scheduling of drip irrigation, as well as guidelines for the application of deficit irrigation to obtain certain grapevine responses is limited, especially in regions where high frequency irrigation is necessary.

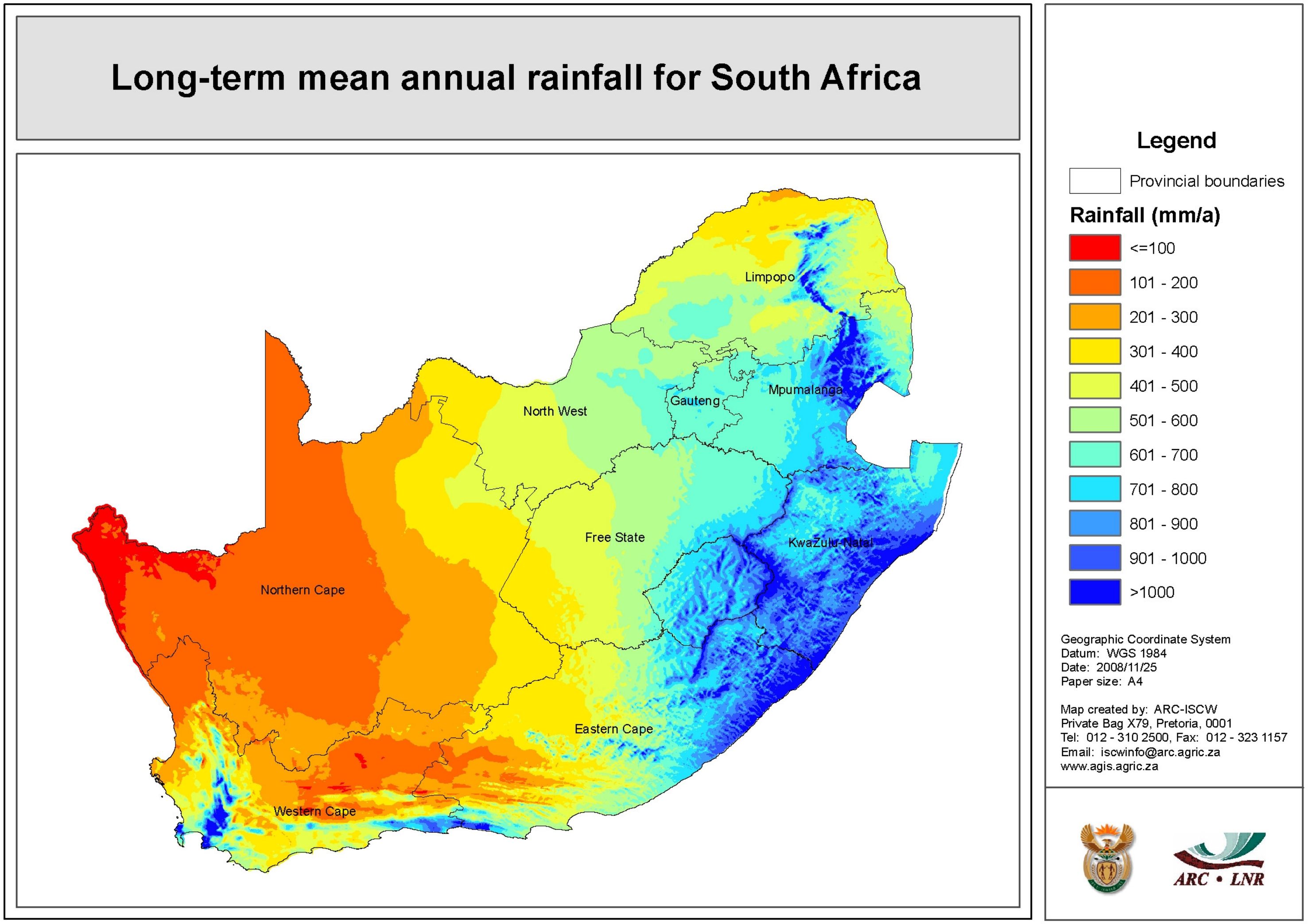

Figure 1.1 Long term mean annual rainfall distribution in South Africa (ARC Institute for Soil, Climate and Water).

1.2 PROJECT AIMS

Apricots, peaches and wine grapes are the primary permanent fruit crops cultivated in the Breede River Valley region in the Western Cape. Due to the low annual rainfall (< 300 mm), and high evaporation rates, this particular region is traditionally regarded a high frequency irrigation area. Consequently, conditions in the Breede River Valley region are more suitable to evaluate different deficit irrigation strategies throughout the growing season compared to the Coastal region of the Western Cape which has a higher rainfall in the first part of the season. This drip irrigation study was part of a project, WW04/23, carried out by the Soil Science Division's Irrigation sub-division of the Agricultural Research Council (ARC) Infruitec-Nietvoorbij and was partially funded by Winetech, *i.e.* the research funding body for the South African wine industry.

The formulated hypothesis was that lower seasonal irrigation volumes would create lower plant water potentials and yields, but better overall wine quality in *Vitis vinifera* L. cv. Shiraz grapevines, compared to ones exposed to high seasonal irrigation volumes.

The aims of the project were:

- To apply ten different deficit irrigation strategies to grapevines in the Breede River Valley;
- To determine the effects of different regulated deficit irrigation strategies on root distribution and density;
- To determine the effects of different deficit irrigation strategies on the plant water status of drip irrigated grapevines;
- To determine the effect of different regulated deficit irrigation strategies on the vegetative growth of drip irrigated grapevines;
- To determine the effects of different deficit irrigation strategies on yield response;
- To determine the effects of different regulated deficit irrigation strategies on the wine quality;
- To determine the effects of different regulated deficit irrigation strategies on the evapotranspiration of drip irrigated grapevines; and
- To use the information generated by this project to compile guidelines for the judicious application of drip irrigation in the Breede River Valley region.

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Chapter 2

LITERATURE REVIEW

THE EFFECT OF WATER CONSTRAINTS ON GRAPEVINE RESPONSE

CHAPTER 2
LITERATURE REVIEW - THE EFFECT OF WATER CONSTRAINTS ON GRAPEVINES

2.1 INTRODUCTION

The grapevine *(Vitis vinifera)* is a temperate climate species adapted to hot summers with mild to cold winters (Williams *et al.*, 1994). Grapevines are cultivated in some of the hottest areas of the earth, between the 30º and 50ºN and 30º and 40ºS latitudes (Williams *et al.*, 1994). In such areas, with low annual rainfall and high evaporation demands, irrigations are usually necessary to produce economically viable crops (Van Zyl, 1981; Williams *et al.*, 1994). The oldest recordings of irrigated viticulture date back to *ca.* 2900 BC in Babylonia and *ca.* 1500 BC in Egypt (Younger, 1966). Grape and wine quality is either affected directly or indirectly by the terroir, relative humidity, wind exposure and soil related factors (Deloire *et al.,* 2005; Bruwer, 2010; Mehmel, 2010). Since world wine markets are increasingly becoming more competitive, it is important to find a balance between optimum yield and wine quality (Mehmel, 2010).

The aim of this literature review is to discuss the effect of water constraints on the grapevine water potential, vegetative growth, yield and its components, as well as on juice and wine quality.

2.2 GRAPEVINE WATER STATUS

In the late 1800's Dixon & Joly (1894) and Askenasy (1895) independently proposed the cohesion theory as the only consistent theory explaining how sap could be lifted ten times higher in a tree than by a vacuum pump. In this theory, the assumption is made that evaporation through the leaves of the tree sucked water through the tree and cavitations were prevented by dimension changes of capillaries in the conductive system. Renner (1911) observed that water could be drawn out of leaves through an artificial stem fastener by means of a vacuum pump. Negative pressures were hereafter frequently indicated by the use of this approach, and a simplified method to measure this negative pressure was described (Scholander *et al.,* 1965). This method involved using a pressure chamber to apply pressure to a leaf and by applying a greater pressure than the pressure with which the plant holds its water in the xylem of the organ, they could quantify the pressure required to force water from the organ. This measurement is generally referred to as the leaf water potential (Ψ_L) when the water withholding capacities or suction in leaves is measured.

Diurnal stress water patterns in grapevines appear when transpiration losses exceed water uptake, even if grapevines are exposed to adequate available water in the soil (Hardie & Considine, 1976). Leaf water potential in grapevines decreases and fluctuates during the day, irrespective of the quantity of water available to the grapevines, with the most negative potential occurring between 12:00 and 14:00 (Van Zyl, 1984; Van Zyl, 1987). Leaf water potential increases at night, and more so, if adequate soil water is available to the plant (Williams *et al*., 1994). Grapevine water status can be influenced by incoming solar radiation, relative humidity, temperature, atmospheric pollutants, wind, soil environment and plant factors (Smart & Coombe, 1983). Choné *et al*. (2001), Lebon *et al.* (2003) and Loveys *et al.* (2004) documented that pre-dawn leaf water potential (Ψ_P) is the reference indicator of soil water potential in many species including grapevines. It was shown that at pre-dawn, each leaf on a grapevine has the same water potential and that this water potential is in equilibrium with the wettest soil layer explored by the root system (Van Leeuwen *et al.*, 2009). Pellegrino *et al.* (2004) also found a good correlation between the Ψ_P measurements of Shiraz and Gewürztraminer and the fraction of transpirable soil water or percentage plant available water (PAW) depletion (Figure 2.1). Furthermore, a reduction in grapevines Ψ_L, stomatal conductance and assimilation rate can be expected when soil water becomes less available (Williams *et al*., 1994; Schultz, 1996; Naor & Bravdo, 2000; Williams & Araujo, 2002; Soar *et al*., 2006; Patakas *et al*., 2005; Pellegrino *et al*., 2005; Van Leeuwen *et al.,* 2009).

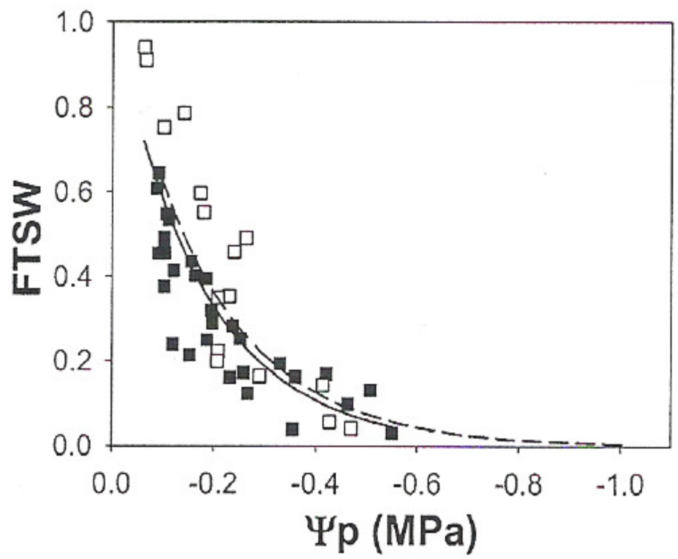

Figure 2.1 Fraction of transpirable soil water (FTSW) plotted against pre-dawn leaf water potential (Ψ_p) in Shiraz (□) and Gewürztraminer (■) (Pellegrino *et al.*, 2004).

Correlations between Ψ_L and grapevine physiology, vegetative growth and yield have been reported (Williams *et al.*, 1994 and references therein). Patakas *et al.* (2005) indicated that a lack of differences between Ψ_L in grapevines subjected to different irrigation treatments could be attributed to isohydric behaviour which causes similar Ψ_L values in irrigated and stressed plants. Stem water potential (Ψ_S) can also be used to quantify grapevine water status. The Ψ_S is measured by covering a leaf using a double lined plastic and aluminium foil bag at least a hour before the measurements (Choné *et al.*, 2001). This potential is considered to be a better indicator of differences in plant water status than Ψ_L (Choné *et al.*, 2001; Williams & Araujo, 2002; Patakas *et al.*, 2005; Van Leeuwen *et al.*, 2009). It was observed that Ψ_L regulation depended on soil water availability and other external factors, such as vapour pressure deficit, leaf intercepted radiation, plant hydraulic conductivity and stomatal regulation (Choné *et al.*, 2001). Due to this, Ψ_S seemed to be the best indicator of soil water availability, followed by Ψ_P. The difference between Ψ_S and Ψ_L ($\Delta\Psi$) was found to be significantly correlated to transpiration flow and can thus be a useful method of estimating transpiration of field grown grapevines (Choné *et al.*, 2001). Furthermore, Ψ_S could also serve as an indicator of hydraulic conductivity in the trunk and shoot sap pathway (Choné *et al.*, 2001).

Threshold values for grapevine water constraint classes based on Ψ_P in Shiraz were proposed (Ojeda *et al.*, 2002). These classes are no stress (> -0.2 MPa), weak stress

(-0.2 MPa to -0.4 MPa), medium stress (-0.4 MPa to -0.6 MPa) and strong stress (< -0.6 MPa. Greenspan (2005) suggested that irrigation applications in California should begin when midday Ψ_L of white grapevine cultivars reaches -0.8 MPa and red cultivars -1.0 MPa. As a general guideline, midday Ψ_L measurements could be classified as no stress (> -1.0 MPa), mild stress (-1.0 MPa to -1.2 MPa), moderate stress (-1.2 MPa to -1.4 MPa), high stress (-1.4 MPa to -1.6 MPa) and severe stress (< -1.6 MPa) (Greenspan, 2005).

Mid-day Ψ_L responses of European cultivars (Chardonnay, Cabernet Sauvignon, Malbec and Shiraz) to drier soil conditions were considerably more prominent compared to native American cultivars (Kaiser *et al.*, 2004). Different plant water potential responses where two European cultivars were exposed to the same two soil water regimes was also reported (Schultz, 1996; Schultz; 2003). Lower Ψ_P and mid-day Ψ_L occurred in non-irrigated Shiraz grapevines compared to that in non-irrigated Grenache at the same locality and soil water regime. Similarly, mid-day Ψ_L in Sauvignon blanc and Pinotage subjected to the same soil water regimes were comparable, but at dryer soil conditions Ψ_P in Pinotage was lower than in Sauvignon blanc (Myburgh, 2011a). Merlot and Shiraz also showed more water constraints compared to Sauvignon blanc under the same soil water regimes and atmospheric conditions (P.A. Myburgh, personal communication, 2010). The difference in stomatal sensitivity between some cultivars and species may limit transpiration to compensate for differences in the vulnerability of xylem cavitation (Jones & Sutherland, 1991). By regulating the stomatal conductivity, some species, *e.g.* maize, cowpea and sugarcane, maintain a near constant Ψ_L throughout the day at a value that is not dependent on the soil water status (Schultz, 2003 and references therein). Such plants are classified as isohydric plants. Other species, like barley and sunflowers will experience a decrease in Ψ_L with an increased evaporative demand during the day and a lower Ψ_L in plants exposed to water constraints than in well-watered plants (Schultz, 2003 and references therein). These species are classified as anisohydric plants. The differences in grapevine response could be attributed to the fact that some grapevine cultivars exhibit stronger isohydric behaviour towards low soil water availability (*e.g.* Grenache). Shiraz tend to be more anisohydric at the same soil water regime (Schultz, 2003). When grapevines are subjected to a soil water deficit, abscisic acid (ABA) is formed in the roots and apoplastic water transport is inhibited (Lovisolo *et al.*, 2010). Near-isohydric grapevines will experience a decrease in root hydraulic conductivity (K_h) and have a stable aquaporin concentration, while anisohydric ones will show a stable root K_h and higher aquaporin concentration (Lovisolo *et al.*, 2010). The cytokinin concentration in shoots of near-isohydric, as well as anisohydric cultivars, is then lowered by the rise of ABA concentration in the grapevine roots due to a cytokinin/ABA antagonism (Thimann, 1992). Within the leaves of near-isohydric grapevines, stomatal conductance and leaf K_h is co-regulated to avoid cavitation in the xylem (Lovisolo *et al.*, 2010). This causes regulation of stomatal conductance and fluctuations in the Ψ_L, whereas more anisohydric cultivars undergo osmotic adjustments and changes in cell wall elasticity which causes a more constant decrease in Ψ_L (Figure 2.2).

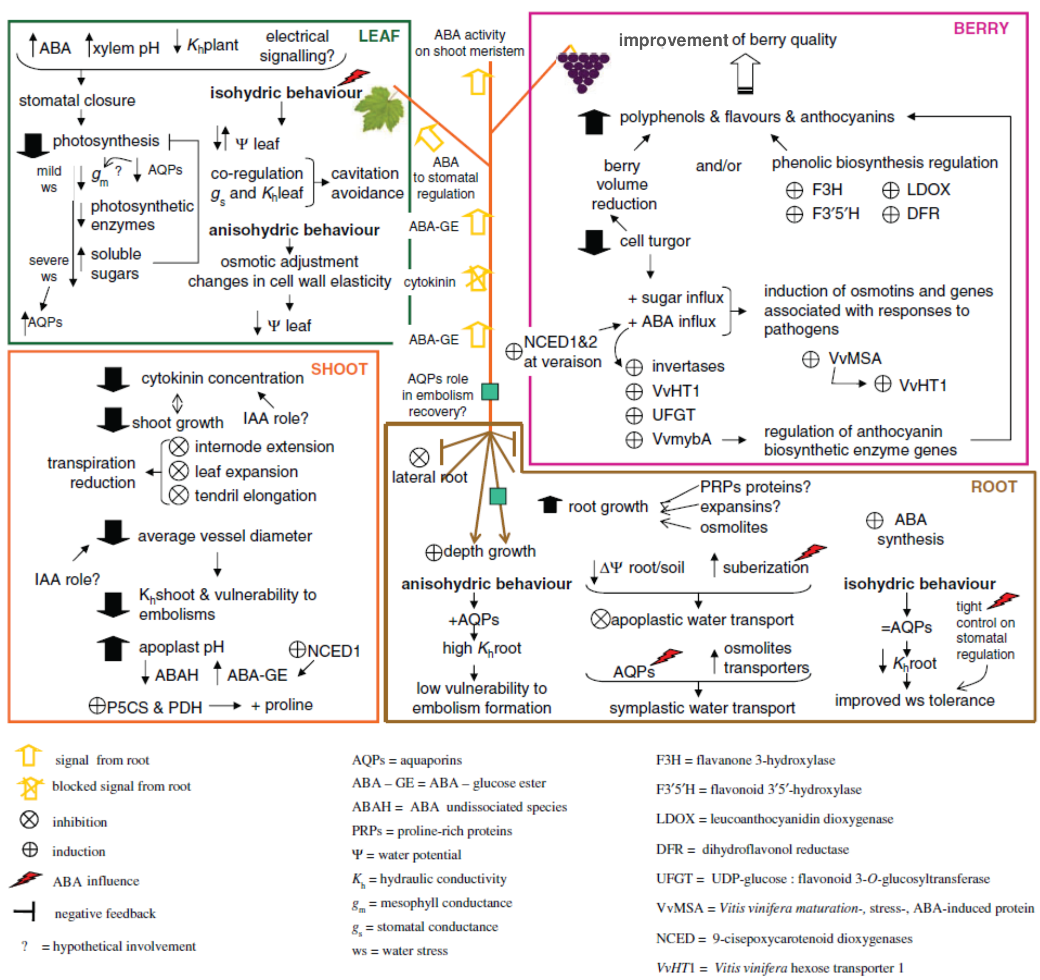

Figure 2.2 Diagram showing the effects of soil water deficits on physiological processes in near-isohydric and more anisohydric reactive grapevines as suggested by Lovisolo *et al.* (2010).

2.3 VEGETATIVE GROWTH

Increased grapevine vegetative growth almost invariably occurs when high soil water availability is maintained by applying more frequent irrigation and/or higher volumes of water compared to ones exposed to water constraints (Van Zyl, 1981; Smart, 1982; McCarthy *et al.,* 1983; Myburgh, 1996; Myburgh, 2003; Myburgh, 2011b, Myburgh, 2011c). Water constraints caused by inadequate plant available soil water have an inhibitory effect on vegetative growth and can alter the grapevine phenology (Coombe & Dry, 1988). Furthermore, active shoot growth may continue throughout the whole season when adequate water is present (Van Zyl, 1981). In dry soil, the inhibition of vegetative growth can be attributed to the rise in ABA and decrease in cytokinin concentrations in the shoots due to the cytokinin/ABA antagonism (Thimann, 1992; Lovisolo *et al*., 2010). In some cases, mild soil water deficits may not have any effect on the vegetative growth of grapevines when compared to ones that are exposed to adequate soil water availability. This effect was found in Muscat d'Alexandrie and Castelão (Santos *et al*., 2003), Mourvédre (De La Hera *et al*., 2007) and Merlot (Lategan & Howell, 2010a).

Adequate water supply during the post-véraison stage may stimulate re-growth of shoots. These actively growing shoot tips compete directly with berries for carbohydrates produced by active green leaves (Saayman, 1992) since the distribution of photosynthetic products is regulated by the source to sink relationship (Johnson *et al*., 1982). Severe water constraints may not only terminate shoot growth, but could cause yellowing of basal leaves will turn and even leaf abscission (Van Zyl & Weber, 1977). Mild grapevine water constraints may stop shoot growth which can improve bunch exposure to sunlight. The termination of shoot growth could have positive implications, particularly for red grape cultivars (Williams *et al*., 1994), where over-shading due to excessive vegetative growth can have a detrimental effect on wine colour (Smart, 1982). For both Colombar (Van Zyl, 1984) and Shiraz (McCarthy, 2000) vegetative growth was most sensitive for soil water constraints during the period following flowering. Colombar grapevines irrigated every seven days throughout the growing season produced a higher pruning mass in comparison to ones that were irrigated every 14 days, 21 days and 28 days (Myburgh, 2007). No further reduction in the pruning mass between the longer irrigation intervals indicated the sensitivity of the vegetative growth of grapevines to moderate or severe soil water constraints compared to no or low constraints. Pinotage and Sauvignon blanc irrigated at ≤50% PAW depletion throughout the growing season produced higher cane mass in comparison to grapevines that were irrigated at a higher readily available water (RAW) depletion level for some period of the season (Myburgh, 2011b). The desired rapid growth during spring followed by a cessation of shoot growth between véraison and ripening can be achieved by means of irrigation manipulations in dry climate (Bravdo & Hepner, 1987). The judicious use of irrigation water can therefore be an important tool to control grapevine vigour in dry climates.

2.4 YIELD COMPONENTS

Grape berry growth can be divided into four stages. Stage I is the herbaceous growth phase that last until 40 to 50 days after flowering (Deloire, 2010). Stage II is called the herbaceous plateau and during this stage berry growth slows down or ceases (Deloire, 2010). Stage III is characterised as the part of the season when berries rapidly expand, start to change colour and soften and this stage corresponds with the start of maturation (Deloire, 2010). During Stage IV, known as maturation, the berry growth rate slows down and comes to a stop.

Small berries can contribute to high wine quality in the case of red grape cultivars (Bravdo *et al*., 1985; McCarthy, 2000; Kennedy *et al*., 2002). Final berry size is most sensitive to water constraints during Stage I of berry development (Van Zyl, 1984; Matthews *et al*., 1986; Williams *et al*., 1994 and references therein). Berry size of Shiraz (McCarthy, 2000) and Pinot noir (Girona *et al*., 2006) was most sensitive for water constraints during the *ca.* four week period after flowering (between flowering and pea size). Where Shiraz grapevines were subjected to water constraints during different periods (Figure 2.3), the smallest berries were produced by strong water constraints between anthesis and véraison (Ojeda *et al*., 2002). Furthermore, a reduction in berry size caused by soil water deficits during Stage I cannot be reversed by more irrigations during Stage II and/or Stage III of berry development (Smart *et al*., 1974; Van Rooyen *et al*., 1980; Ojeda *et al*., 2002).

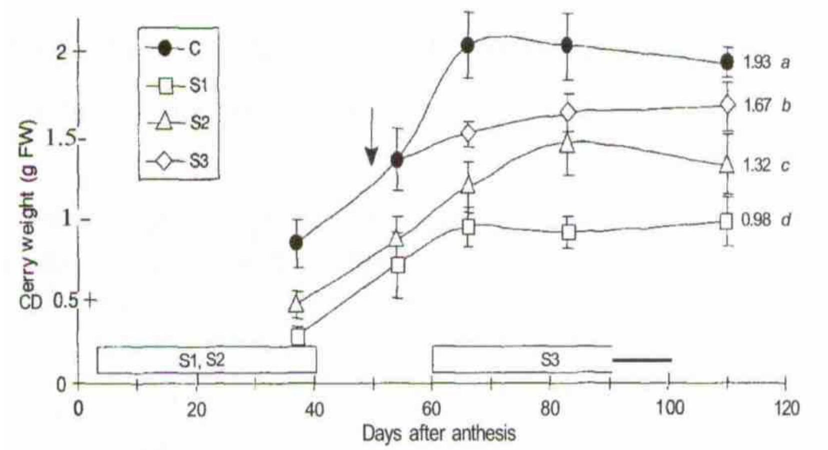

Figure 2.3 Changes in fresh weight (FW) (g) of Shiraz berries subjected to water deficit treatments as a function of number of days after anthesis. C = control; S1 = strong; S2 = medium levels of early water deficit between anthesis (flowering) and véraison; S3 = strong late water deficit between véraison and harvest maturity. Arrow indicates onset of véraison. Vertical bars indicate standard deviation (n = 6). Values followed by the same letter are not significantly different ($p < 0.05$) (Ojeda *et al.,* 2002).

The duration and timing of water constraints can also influence final berry size. Irrigation at *ca*. 80% readily available water (RAW) depletion throughout the season reduced Pinotage berry size compared to 50% depletion, but irrigation at 80% depletion either before véraison or after véraison had no effect on berry mass (Myburgh, 2011d). Sauvignon blanc berry size responded similarly, except that irrigation at *ca*. 50% RAW depletion before véraison followed by 80% depletion during berry ripening also reduced berry mass (Myburgh, 2011e). In the case of the latter irrigation strategy, berries shrunk when the grapevines were suddenly exposed to high soil water deficits (Myburgh, 2011e). Grapevine manipulation by means of management practices, *e.g.* the use of vigour reducing rootstocks, canopy manipulations by means of different trellis systems and management practices are not necessarily sufficient to ensure smaller berries (Ellis, 2008). Based on this, it was concluded that irrigation strategy plays an important role in the manipulation of berry size (Ellis, 2008).

In summer, different irrigation strategies have no effect on the number of bunches per grapevine produced. The number of bunches per grapevine is a direct result of the winter pruning method and a negative linear relationship can be expected between the number of bunches per grapevine and mean bunch mass (Ashley, 2004). Severe water constraints during winter, in combination with very low relative humidity of the atmosphere, may also affect the number of bunches produced in the following growing season (Myburgh, 2008).

Irrigation improved fruit set and increased berry size of Chenin blanc grapevines which reflected in bigger bunches compared to rain-fed grapevines (Van Zyl & Weber, 1977). Previous research also showed that where Pinotage and Sauvignon blanc grapevines were irrigated at *ca.* 50% RAW depletion before and *ca.* 80% RAW depletion after véraison, lower bunch masses were obtained compared to those irrigated at *ca.* 50% RAW depletion throughout the season (Myburgh, 2011d; Myburgh, 2011e). The smaller berries seemed to be a function of berry shrinkage due to the sudden water constraints experienced by the grapevines. Bunch mass of Merlot in the Coastal region of South Africa also seemed to be related to the volume of irrigation water applied via its effect on berry mass (Myburgh, 2011c).

In the Stellenbosch area, a single irrigation increased Chenin blanc yields compared to non-irrigated grapevines (Van Zyl & Weber, 1977). However, additional irrigations did held no further advantage on yield. Irrigating Colombar in the lower Orange river region every week to field water capacity (FC) increased yield compared to irrigation to FC every 14, 21 or 28 days, respectively (Myburgh, 2007). Where Pinotage was irrigated at *ca.* 50% RAW depletion throughout the season or irrigated at *ca.* 80% RAW depletion before véraison followed by *ca.* 50% RAW depletion during ripening tended to produce higher yields in the Breede River Valley region (Myburgh, 2011d). Pinotage grapevines that were irrigated at *ca.* 80% RAW depletion during ripening tended to produce lower yields (Myburgh, 2011d). Merlot yields in the Breede River Valley (Lategan & Howell, 2010b), as well as Coastal regions (Myburgh, 2011c) of South Africa increased with increasing precipitation (*i.e.* rain plus irrigation) in the growing season until it reached a plateau. Following this point, no further yield increases were obtained with increased precipitation. It is evident from previous research that yield seems to be a stronger function of berry mass than bunch mass, *i.e.* higher yields could be expected if berry masses are higher (Ashley, 2004).

2.5 JUICE CHARACTERISTICS

Luxurious water supply to grapevines during ripening is well known to stimulate vegetative re-growth as discussed in Section 2.3. These actively growing shoots compete with berries for carbohydrates synthesised in green leaves and reduces availability for sugar in the berries (Saayman, 1992). According to Van Zyl (1981), a higher sugar concentration can be expected in the juice of non-irrigated grapevines or ones that receive little irrigation compared to grapevines that receive more irrigation in the same climatic region. The beneficial effect of mild water constraints during ripening on grape and wine quality (Van Zyl & Weber, 1977) is probably caused by the reducing effect of water constraints on vegetative growth (Smart & Coombe, 1983). In contrast, severe water stress can retard sugar accumulation (Smart & Coombe, 1983). No significant differences were present in the final sugar concentration between frequently irrigated and deficit irrigated Shiraz grapevines (Ojeda *et al.*, 2002). The total soluble solids per berry were proportional to berry size as quantified in terms of berry mass. Similarly, different levels of water constraints during berry ripening (Myburgh, 2005) had no effect on the sugar concentration in Sauvignon and Chenin blanc grapes at harvest in the Stellenbosch region (Myburgh, 2006a).

High wine pH has a negative effect on the colour intensity of red wines and the aging potential of the wine (Ribéreau-Gayon *et al.,* 1998). Luxurious irrigation not only slows berry ripening, but elevates juice pH and reduces acidity (Smart & Coombe, 1983). Grape juice with a high potassium (K) concentration tends to have a high pH and high malate concentration and these malate concentrations may decrease during the vinification process causing a further pH increase (Jackson & Lombard, 1993). Dense grapevine canopies caused by high irrigation frequencies, *i.e.* high levels of plant available water, will induce excessive shading in the bunch zone (Jackson & Lombard, 1993). Under such conditions, K would be more readily absorbed and transported through the plant to the fruit, causing higher juice pH. Where Cabernet Sauvignon grapevines received 100% of their seasonal water requirement, pH, tartaric acid, malic acid and K concentration in the juice was higher compared to grapevines that only received 70% or 50% of their seasonal water requirement (Prichard & Verdegaal, 1988).

The organic acid content of grape berries consists mainly of tartaric, malic and citric acids (Ribéreau-Gayon *et al.*, 1998). Total titratable acidity (TTA) is an important quality factor since wine containing too high acidity is tart in taste, whereas wine containing low acidity may produce a bland taste. Micro-organism activity becomes more likely in high pH wines (Ribéreau-Gayon *et al.,* 1998). The malic and tartaric acid concentrations in grape berries are highest between pea size and véraison (Van Zyl, 1984; Hunter *et al.*, 1991; Hunter & Ruffner, 2001). During berry ripening, malic acid levels decrease (Van Zyl, 1984; Iland & Coombe, 1988; Hunter *et al.*, 1991; Coombe, 1992) due to malic acid metabolism (Iland & Coombe, 1988), whereas the tartaric acid concentration remains constant (Van Zyl, 1984). In California, Cabernet Sauvignon grapevines that received the "minimal irrigation", *i.e.* only 32 L per grapevine once Ψ_L reached -1.6 MPa, produced the highest TTA and lowest pH, respectively, compared to grapevines that received 32 L and 64 L per grapevine per week, irrespective of Ψ_L (Chapman *et al.*, 2005).

2.6 WINE QUALITY CHARACTERISTICS

Soil water status may induce substantial differences in leaf and canopy development causing conditions varying from excessively shaded to highly exposed bunches (Ellis, 2008). A reduction of berry size will result in less compact bunches and in conjunction with a more open canopy, a greater surface area of such berries would be exposed to sunlight (Ellis, 2008). The higher sunlight exposure within and around bunches may improve the colour of grape berries and subsequently the wine (Smart, 1982). Phenolic compounds which produce the unique cultivar tastes, mainly occur in the skin and seeds of the grape berry (Ojeda *et al.*, 2002). Flavonoid compounds in grape berries, particularly anthocyanins and flavanols, are major contributors to wine colour (intensity and stability), astringency and wine flavour (Ristic *et al.*, 2010). The final berry size indirectly affects the phenolic concentrations of the juice since the concentration depends on the skin surface-to-berry volume ratio (Singleton, 1972; Ojeda *et al.*, 2002). Higher concentrations of anthocyanins and skin tannins in berries, coupled with a lower seed tannin concentration were associated with higher wine quality (Ristic *et al.*, 2010). It was suggested that the ratio of (anthocyanins x skin tannins)/seed tannins could be used as an indicator of wine flavonoids, wine colour and wine quality.

The anthocyanin concentration of Shiraz berries is most sensitive to luxurious water supply during ripening (Ojeda *et al.*, 2002). The highest phenolic concentrations in Shiraz grapes juice are obtained by no irrigation, to very little irrigation during ripening (Petrie *et al.*, 2004). Similarly, anthocyanin concentrations in Pinotage wines tended to be higher in wines made from grapes irrigated at *ca.* 80% RAW depletion compared to ones irrigated at *ca.* 50% RAW depletion (Myburgh, 2006b). It was found that highest concentrations of phenolics and anthocyanins in Shiraz wines were obtained with non-irrigation grapevines compared to ones receiving drip irrigation with crop coefficients of 0.2 or 0.4, respectively (McCarthy *et al.*, 1983). Pinot noir grapevines that experienced soil water deficits during ripening also produced the highest concentrations of anthocyanins and polyfenols (Girona *et al.*, 2006). Similarly, Cabernet Sauvignon grapevines exposed to high soil water deficits produced higher juice phenolic concentrations and extracted phenols and anthocyanins of berry skins, compared to frequently irrigated grapevines (Matthews *et al.*, 1987). Shiraz grapevines that received excessive water during the growing season, but where the canopies were managed to allow high bunch exposure to sunlight, produced wines containing only 70% of the total anthocyanins and tannins in wines where grapevines were exposed to water deficits (Ristic *et al.*, 2010).

Müller-Thurgau grapevines, grown in pots and subjected to high soil water deficits during ripening produced wine which was rated as "fruity, fragrant and elegant", compared to the "full-bodied and less elegant" wine obtained where water availability adequate (Becker & Zimmerman, 1983). Wines least preferred were those produced from grapevines that were subjected to dry soil conditions until véraison followed by wet soil conditions during ripening. Semillon grapevines that had excessive water available produced wines with a grassy taste, whereas a more fruity taste was present in wine made of grapevines that were subjected to soil water deficits (Ureta & Yavar, 1982). In a study on the effect of irrigation in a warm climate on grape juice flavour and aroma as perceived by a tasting panels, non-irrigated grapevines produced juice containing higher levels of potential volatile terpenes (McCarthy & Coombe, 1984). Non-irrigated grapevines also produced wines with higher sensorial quality scores (McCarthy *et al.*, 1986). Cabernet Sauvignon growing in sandy soils in a hot climate produced wines with the highest berry character and overall quality if adequate irrigation water is applied during the growing season (Bruwer, 2010). In cooler climates or in loamy soils with higher soil water holding capacities, better cultivar character and overall quality can be expected when medium to high water constraints occur in Cabernet Sauvignon grapevines (Bruwer, 2010). During dry growing seasons, Merlot grapevines produced better wine colour, cultivar character and overall wine quality when three irrigations were applied to restore the soil to field water capacity in the Coastal region of South Africa (Myburgh, 2011c). In these dry growing seasons, particularly ones following low rainfall winters, non-irrigated grapevines were exposed to excessive stress and produced inferior wines. Wine colour and overall quality was negatively affected when more than three irrigations were applied per season. Pinotage and Sauvignon blanc grapevines in the semi-arid Breede River Valley region of South Africa, irrigated at *ca.* 80% RAW depletion during ripening, produced the best overall quality wines (Myburgh, 2011d; Myburgh, 2011e). Pinotage grapevines irrigated at *ca.* 80% RAW depletion before véraison and at *ca.* 50% RAW depletion after véraison, produced wines with the lowest anthocyanin concentration, cultivar character and overall quality (Myburgh, 2011d). Sauvignon blanc grapevines irrigated at *ca.* 50% RAW depletion during ripening tended to give a higher sensorial vegetative or grassy wine character (Myburgh, 2011e). Where canopy management were applied so that the bunches were either fully shaded, moderately exposed or fully exposed to sunlight, luxuriously irrigated Shiraz grapevines produced wines characterised by herbaceous and straw aromas (Ristic *et al.*, 2010). On the other hand, wines had a dominant liquorice (spicy) character aroma where grapevines were subjected to soil water deficits, and bunches were fully exposed. Neither irrigated, nor canopy management had an effect on the berry aroma (raspberry and cherry) in the wines.

2.7 SUMMARY

Plant water status is a good indicator of grapevine responses to soil water availability and other environmental and cultivar specific factors. Grapevine water status will respond more negatively as soil water becomes less available for plant uptake and use. Leaf water potential has been used as a indicator of plant water status for many years, but during the new millennium Ψ_P has been preferred as an indicator of plant water constraints. However, it has been found that Ψ_S is a much more reliable indicator of constraints since Ψ_P and Ψ_L measurements can negate differences due to the near-isohydric behaviour of some cultivars. Consequently, Ψ_L thresholds for irrigation management could be cultivar or region bound.

Mild water constraints are necessary before véraison to inhibit vegetative growth during the period of ripening. This would stop actively growing shoot tips from competing with ripening grapes for photosynthetic products. Severe water constraints in grapevines should be avoided between flowering and véraison. Severe stress during this period will have a negative effect on berry size, yield and acid content in the berries. Moderate water stress during the first stage of berry development would result in small berries and looser bunches, with no detrimental effect on the final yield. Luxurious water availability during ripening will result in higher pH, lower titratable acidity as well, as lower anthocyanins and phenols in grape juice. As a result non-cultivar characteristic or low quality wines could be expected if grapevines are luxuriously irrigated, particularly during ripening.

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Chapter 3

THE EFFECT OF DIFFERENT IRRIGATION STRATEGIES ON THE EVAPOTRANSPIRATION AND CROP COEFFICIENTS FOR SHIRAZ VINEYARDS IN THE BREEDE RIVER VALLEY REGION

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3.1 INTRODUCTION

Grapevines are often cultivated in regions with low rainfall and high evaporative demands, and if summer rainfall is erratic or irrigation water limited in these areas, grapevines may experience some water stress during the growing season (Williams *et al*., 1994). Different climatic and viticultural factors can contribute to grapevine water usage and requirements (Myburgh, 1998). Since prevailing climatic conditions may vary between different regions or areas, different irrigation strategies need to be adopted in each area to ensure economically viable yields and grape quality for wine production (Bruwer, 2010).

In many previous grapevine irrigation studies, different irrigation levels were obtained by applying irrigations at different fractions of reference evapotranspiration (ET_o) or crop coefficients (K_c) (McCarthy *et al*., 1983; Ojeda *et al*., 2002; Kaiser *et al*., 2004; El-Ansary *et al*., 2005; Patakas *et al*., 2005; Scholasch *et al*., 2005; Tarara *et al*., 2007; Olivo *et al*., 2009). Different treatments were also induced by applying irrigation as a percentage of the water that a control treatment received (Ojeda *et al*., 2002; Kaiser *et al*., 2004; Chapman *et al*., 2005; Chaves *et al*., 2007). Another approach is refilling the soil profile back to field water capacity (FC) at certain physiological stages (Van Zyl, 1975; Hunter & Deloire, 2001; Ojeda *et al*., 2002; Myburgh, 2005; Ellis, 2008) or within a specific time frame (Myburgh, 2006). Since it is not always stated how many water was still available for grapevine uptake when the irrigation was applied, there is some doubt around the applicability of such treatments. For example, irrigation applied in a semi-arid climate region at 0.75 of ET_o can be refilling of the soil water content with 75% of the ET_o on a daily, weekly or three weekly basis or any time in between. The longer the soil is allowed to dry out, the lower the soil water matric potential (Ψ_m) will be and the higher the water stress that could affect grapevine physiology (Williams *et al*., 1994). Nieuwoudt (1962), Van Zyl (1984; 1988), Myburgh (1996; 2006; 2011) and Pellegrino *et al*. (2004) have all used fractions of soil water availability, either readily plant available water (RAW) or total plant available water (PAW), to which the soil was allowed to dry out before a refill irrigation back to FC was applied. This enabled the determination of crop coefficients for different depletion levels in different climatic regions for different irrigation strategies. Following this approach, the research was less scenario-bound since treatments, and in some way results, became applicable in other areas as soil characteristics were the main criteria for irrigation applications. Van Zyl (1984) did however found that Colombar grapevines in the Breede River Valley irrigated at 10% PAW depletion level by means of micro-sprinkler irrigation needed *ca.* 200 mm more water compared to grapevines irrigated at the same depletion level by means of drip irrigation. This indicate that irrigation system type can have a big influence on the water requirement of grapevines.

In South Africa, most of the previous irrigation research on grapevines was carried out on full surface flood, overhead sprinkler or micro-sprinkler irrigation irrigated vineyards (Van Zyl & Weber, 1977; Van Zyl, 1984; Myburgh, 1996; Myburgh, 1998; Myburgh, 2003; Myburgh, 2006; Myburgh, 2011). Therefore, knowledge on the effects of drip irrigation on grapevines is limited (Van Zyl, 1988). With water being a scarce resource and with the potential water savings associated with drip irrigation, a research project was initiated to determine the effects of different drip irrigation strategies on Shiraz grapevines. The aim of this chapter is to determine the effect of ten different drip irrigation strategies on the water use of Shiraz grapevines in a semi-arid region.

3.2 MATERIALS AND METHODS

3.2.1 Experiment vineyard

The field experiment was carried out in a commercial vineyard (S 33°54′04″, E 19°40′33″) *ca.* 23 km southwest from Robertson on the farm Wansbek in the Agterkliphoogte ward of the Breede River Valley region (Figure 3.1). The vineyard was situated on the flood plane of the Poesjenels River on a southeast facing slope (<1°) at an altitude of 201 m above sea level. The region has a cool semi-arid climate (Peel *et al.*, 2007) and based on the growing degree days (GDD), from 1 September until 31 March (Amerine & Winkler, 1944), the specific locality is in a class V climatic region (Le Roux, 1974). Shiraz (*syn.* Syrah) (clone SH1A) grapevines, grafted onto

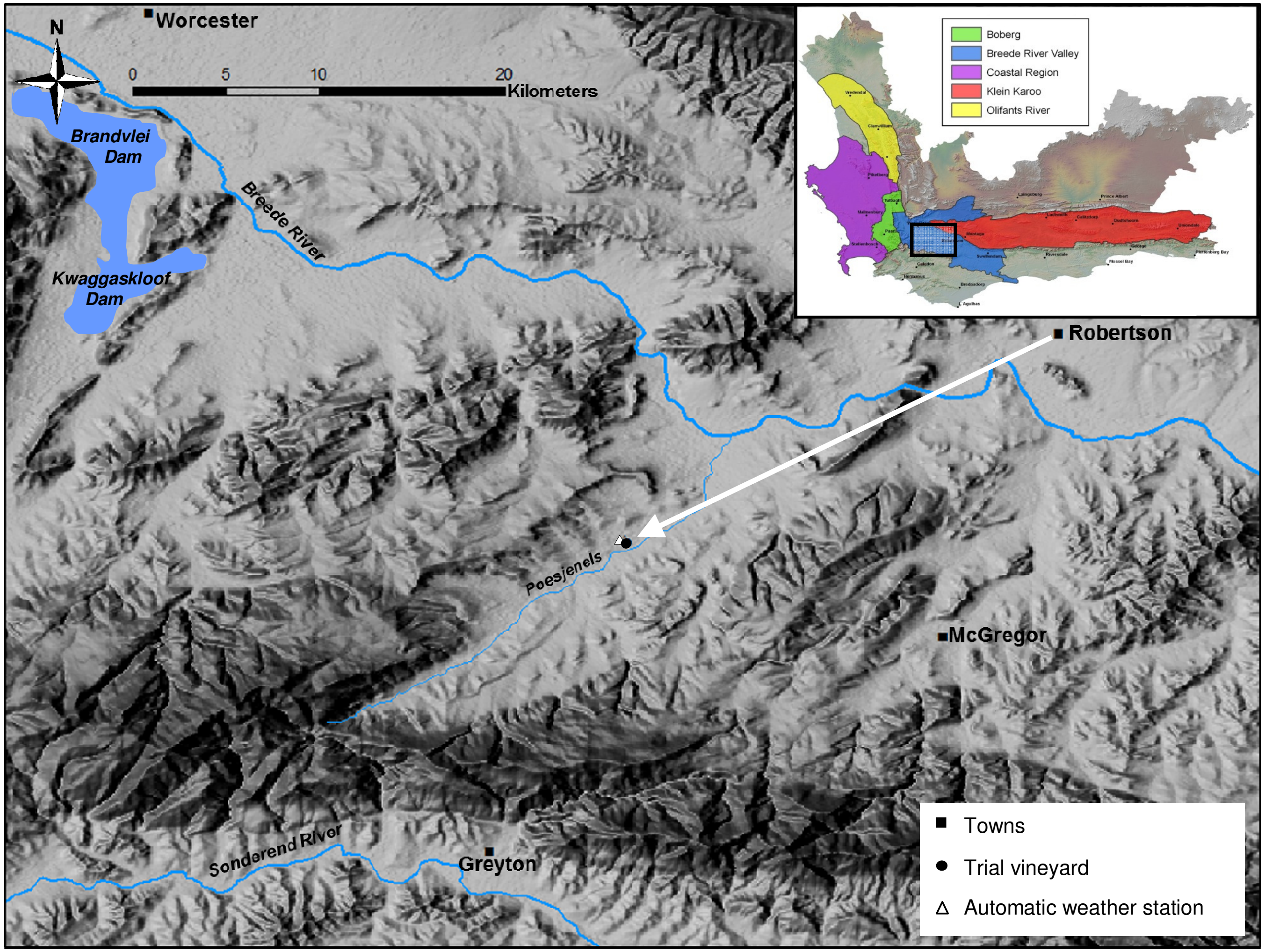

Figure 3.1 Map indicating the locality of the Shiraz/110R experimental vineyard near Robertson.

110 Richter (*Vitis berlandieri* x *Vitis rupestris*), were planted in August 2000 in a northwest/southeast row direction after the soil was double delved (cross-ripped) to a depth of 0.8 m during soil preparation (Van Huyssteen, 1983). Grapevines were planted 2.5 m by 1.2 m and trained onto a four strand lengthened Perold trellis system (Booysen *et al.*, 1992) (Figure 3.2). Before the field trial started, irrigations were applied on a weekly basis during the growing season by means of 1.2 m spaced 4 L/h drippers (Andrag, Bellville). Grapevines were pruned to two bud spurs at *ca.* 12 cm intervals to allow five spurs for each of the two cordon arms. In September, *i.e.* at bud break, the experimental grapevines received the same annual fertilizer application as the rest of the commercial block. Fetilization amounted to 150 kg/ha KNO_3 applied by hand under the drippers and leached into the soil profile by means of a 12 hour irrigation. Suckering, *i.e.* the removal of excess shoots not growing on spurs, was performed before flowering. Shoots were tucked into the trellis wires before the end of October. Topping of active growing shoot tips was carried out in the beginning of December.

3.2.2 Experiment layout

Ten irrigation strategies were applied by means of a drip irrigation system from bud break in September until harvest in March (Table 3.1). Treatments were applied for three seasons, namely 2006/07, 2007/08 and 2008/09. Grapevines of the control treatment (T1) were irrigated at 30% to 40% PAW depletion throughout the growing season. Plant available water was seen as the soil water content between field capacity and permanent wilting point. Three treatments were irrigated at 70% to 80% PAW depletion from bud break till véraison [when *ca.* 95% of grape berries have changed colour - equivalent to stage 36 of the modified Eichhorn and Lorenz grapevine growth identification system (Coombe, 1995)], followed by either irrigation at 30% to 40% PAW depletion (T2) or a continuous deficit irrigation (CDI) strategy (T3) or irrigation at 70% to 80% PAW depletion (T4) during ripening. The CDI strategy was obtained by applying *ca.* half the volume of water that was applied to the control. This allowed the soil to dry out gradually between physiological stages (bud break and véraison or véraison and harvest). Three further treatments were irrigated at *ca.* 90% PAW depletion from bud break until véraison, followed by irrigation at 30% to 40% PAW depletion (T5) or a CDI strategy (T6) or irrigation at *ca.* 90% PAW depletion (T7) during ripening. Grapevines of two treatments were irrigated by means of a CDI

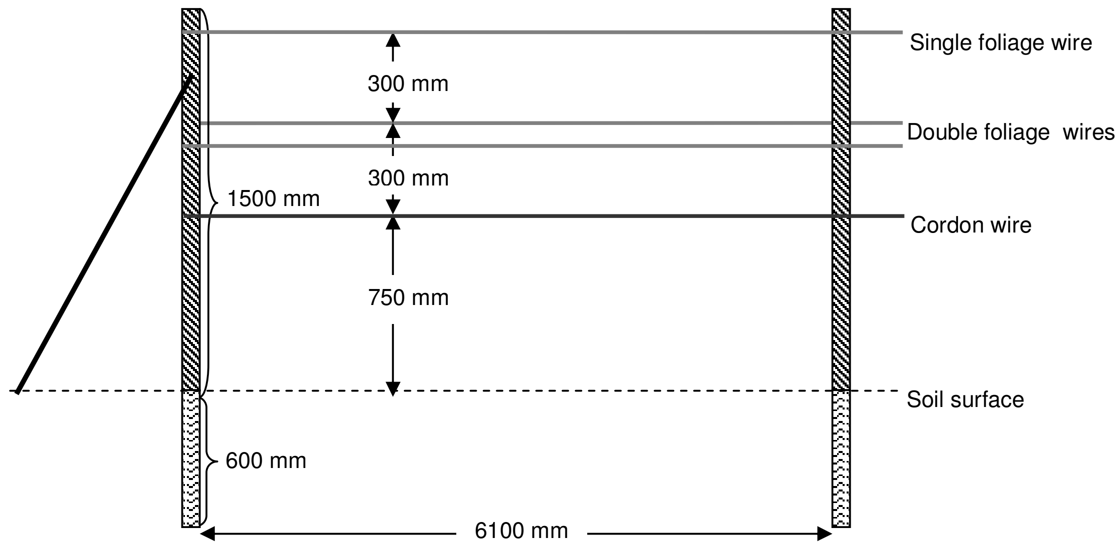

Figure 3.2 Schematic illustration of the dimensions of the four strand lengthened Perold trellis system (Booysen *et al*., 1992) of the experimental vineyard near Robertson (not drawn to scale).

Table 3.1 Different irrigation strategies applied to Shiraz/110R grapevines growing in a sandy loam soil during the 2006/07, 2007/08 and 2008/09 seasons near Robertson.

Treatment number	Treatment abbreviation	Irrigation strategy	
		Pre-véraison	Post-véraison
T1	35%→35%	30% to 40% PAW[2] depletion	30% to 40% PAW depletion
T2	75%→35%	70% to 80% PAW depletion	30% to 40% PAW depletion
T3	75%→CDI	70% to 80% PAW depletion	Continuous deficit irrigation
T4	75%→75%	70% to 80% PAW depletion	70% to 80% PAW depletion
T5	90%→35%	*ca*. 90% PAW depletion	30% to 40% PAW depletion
T6	90%→CDI	*ca*. 90% PAW depletion	Continuous deficit irrigation
T7	90%→90%	*ca*. 90% PAW depletion	*ca*. 90% PAW depletion
T8[1]	CDI	Continuous deficit irrigation	Continuous deficit irrigation
T9	CDI→CDI	Continuous deficit irrigation	Continuous deficit irrigation
T10[1]	90%→PPR	*ca*. 90% PAW depletion	Partial profile refill

[1] Not refilled to field capacity at véraison.
[2] Plant available water.

strategy from bud break until véraison. For both treatments, the soil water contents (SWC) was allowed to dry out gradually until *ca.* 90% PAW depletion was reached. After véraison, the SWC of the one treatment was maintained at *ca.* 90% PAW depletion by applying only four small irrigations of three hours each during ripening (T8). The soil of the other treatment, received an irrigation at véraison to refill the SWC to field capacity (T9) followed by the CDI strategy during ripening. Grapevines of the tenth treatment were irrigated at *ca.* 90% PAW depletion between bud break and véraison followed by a partial profile refill (PPR) strategy during ripening (T10). In order to obtain a PPR strategy, SWC was maintained only between a 40% and 60% PAW depletion. During the post harvest period and winter months, grapevines were irrigated only when SWC was less than 80% PAW depletion.

All treatments were replicated three times in a randomised block design (Figure 3.3). The first replication of treatments was allocated furthest away and third replication closest to the river to account for possible soil differences that could have occurred towards the Poesjenels River. Experiment plots comprised two rows of six experiment grapevines with two buffer grapevines at each end and a buffer row on each side (Figure 3.4). Each experiment plot covered 122 m^2.

A manifold was tapped into the farm's main irrigation line to obtain water to irrigate the experiment grapevines (Figure 3.5). This manifold consisted of five solenoid valves (Bermad, Macsteel, Bellville) which each controlled a designated irrigation strategy as explained above. A network of 25 mm polyethylene pipe and manual ball valves enabled these solenoid valves to control ten different irrigation strategies before véraison and during ripening. Subsurface blind 20 mm Ø polyethylene pipe was used to connect the manifold outlets to the 17 mm Ø drip lines (3.5 L/h RAM, Netafim, Kraaifontein). The drippers were spaced 1.0 m apart in the laterals on the grapevine rows (Figure 3.4).

R3T5	R3T7	R3T8	R3T4	R3T9	Replicate 3
R3T1	R3T2	R3T3	R3T10	R3T6	
R2T8	R2T6	R2T7	R2T5	R2T3	Replicate 2
R2T4	R2T10	R2T1	R2T9	R2T2	
R1T9	R1T5	R1T4	R1T7	R1T10	Replicate 1
R1T6	R1T3	R1T2	R1T8	R1T1	

Figure 3.3 Experiment layout of the field trial where Shiraz/110R grapevines were subjected to ten different drip irrigation strategies near Robertson.

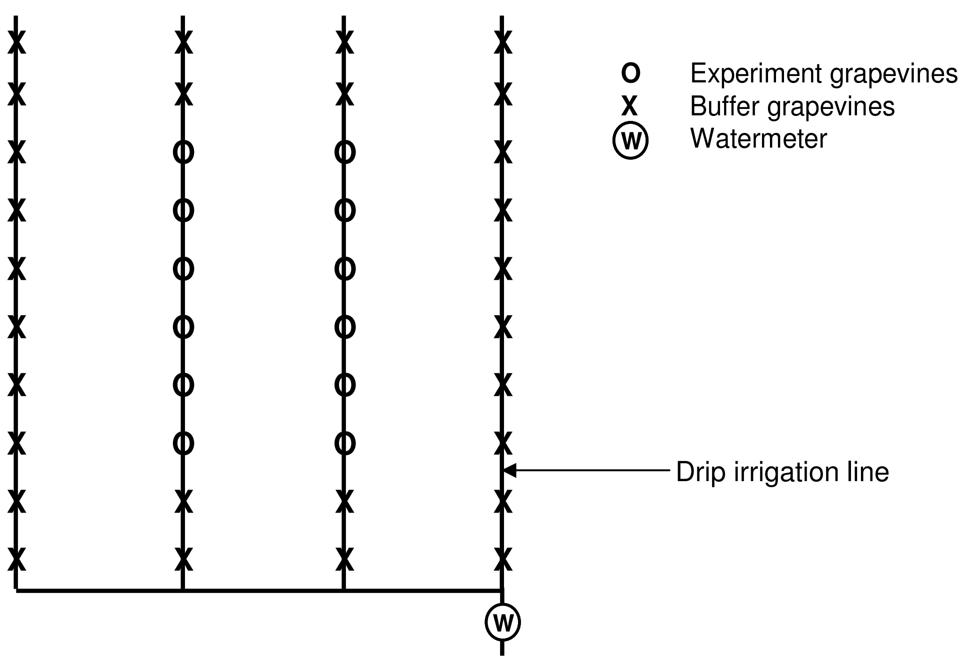

Figure 3.4 Schematic illustration of an experiment plot.

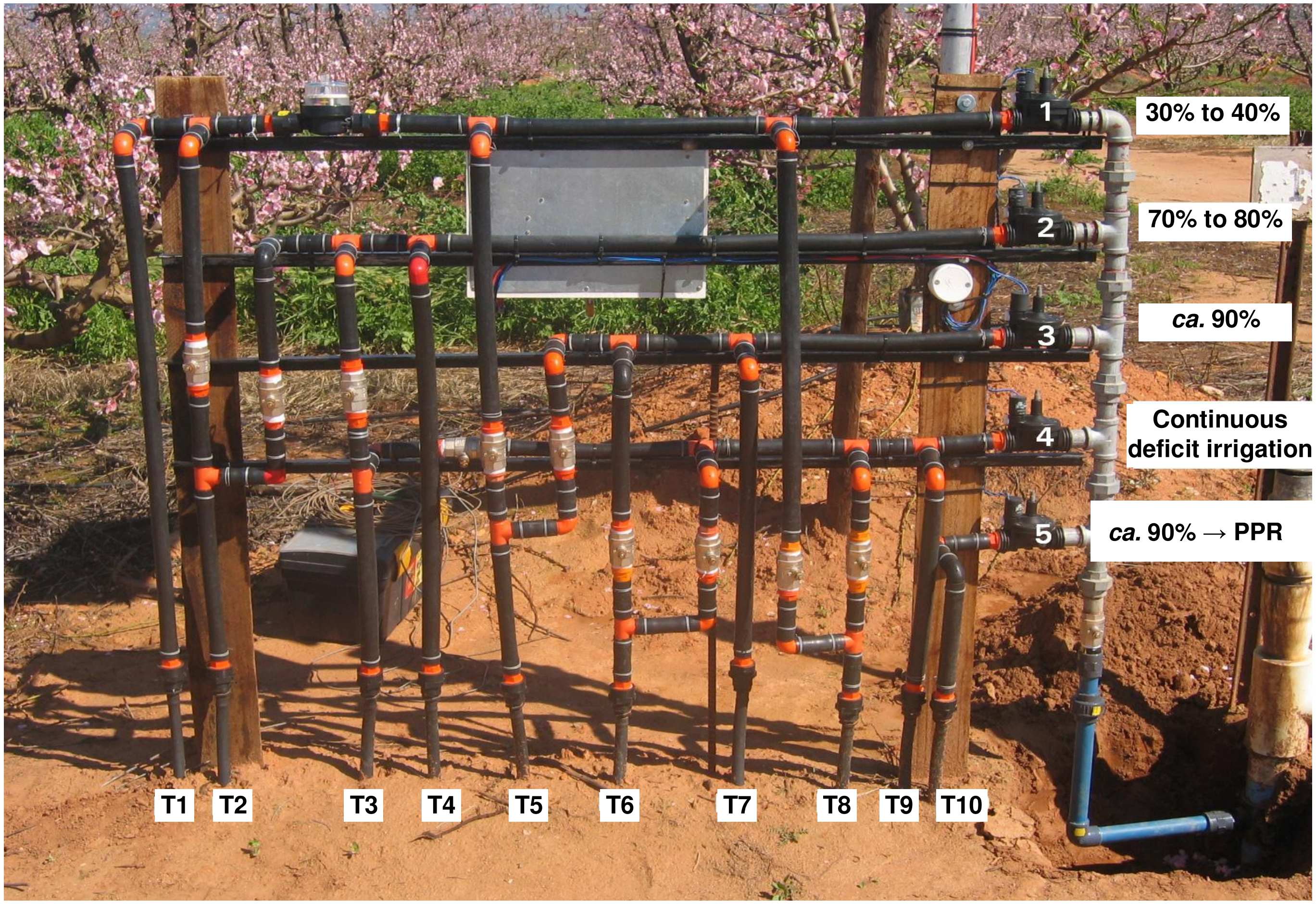

Figure 3.5 Manifold used in the field experiment to apply ten different irrigation strategies to Shiraz/110R in a fine sandy loam soil near Robertson. Solenoid valve 1 controlled treatments that were irrigated at 30% to 40% plant available water (PAW) depletion, valve 2 controlled treatments irrigated at 70% to 80% PAW depletion, valve 3 controlled treatments irrigated at *ca.* 90% PAW depletion, valve 4 those irrigated by means of a continuous deficit irrigation strategy and valve 5 controlled the irrigation of T10, *i.e.* irrigation at *ca.* 90% PAW depletion pre-véraison followed by the partial profile refill strategy during ripening. Manual ball valves allowed different combinations of treatments to be irrigated simultaneously.

3.2.3 Atmospheric conditions

The climate of the region was described using long-term air temperature, relative humidity (RH), reference evapotranspiration (ET_o), net solar radiation, wind speed and rainfall data for a weather station at Le Chasseur, *ca*. 6.2 km from the experiment vineyard. These weather data were obtained from the ARC Institute for Soil, Climate and Water in Pretoria. The prevailing weather conditions during the study period, *i.e.* from September 2005 until August 2009, was recorded by means of a automatic weather station (MC Systems, Cape Town) installed *ca*. 110 m from the experiment vineyard. The weather station hourly recorded air temperature (dry ball and wet ball in a Stevenson screen), incoming solar radiation and wind speed and wind direction. Hourly data were used to calculate the daily maximum, minimum and mean air temperatures, daily maximum, minimum and mean relative humidity of the atmosphere, daily incoming solar radiation and mean daily wind speed. Rainfall was recorded on a daily basis by means of a rain gauge at the automatic weather station.

3.2.4 Soil description and classification

During October 2009, a soil profile pit was excavated in each experiment plot for the purpose of root studies (will be discussed in 4.3.1). The soil was also described and classified according to the South African Soil Taxonomy System (Soil Classification Working Group, 1991) using the soil code approach as described by Lambrechts *et al.* (1978).

3.2.5 Soil chemical and physical status

During June 2006, *i.e.* before the field trial started, six evenly spaced soil profile pits were excavated to determine the root depth of the grapevines. Soil samples were collected at 0 to 300 mm and 300 to 700 mm depth layers to quantify the soil texture of these soil layers, since visual observation revealed that >95% of the roots occurred in the top 600 mm soil layer. The clay and silt fractions was determined by a commercial laboratory (BEMLAB, Strand) according to the hydrometer method (Van der Watt, 1966). The suspension used in the hydrometer method was poured through a 0.25 mm sieve and rinsed under a running tap. The transferred material on the sieve was dried at 100ºC overnight. The dried material was then sieve through 0.50 and 0.25 mm sieves and weighed to determine the coarse and medium sand fractions, respectively. The fine sand fraction was determined by the subtracting the percentage of the clay, silt, coarse sand and medium sand fractions from 100%. Soil texture was classified according to a texture chart (Soil Classification Working Group, 1991). Soil bulk density (ρ_b) was determined in the 0 to 300 mm, 300 to 600 mm and 600 to 900 mm layers. In each layer two 28 x 10^{-5} m^3 undisturbed soil cores were extracted and dried in an extractor oven for 18 hours until a constant mass was attained as described by Blake and Hartge (1986). Cores were weighed to obtain the dry mass and ρ_b was calculated as follows:

$$\rho_b = \frac{\text{Mass of dry soil}}{\text{Volume of cylinder used}} \qquad (3.1)$$

Soil samples were collected in October 2009 after the completion of the field trial to determine if any plant nutrient deficiencies were present and to quantify the effect of the different irrigation strategies on the soil chemical status. Soil pH, phosphorus, exchangeable cations (sodium, potassium, calcium & magnesium) and organic carbon content were determined. The soils were analysed by BEMLAB. Soil pH was determined in a 1 M KCl solution by means of a pH meter. The samples for determination of P content were prepared according to the Bray II method and analysed by an ICP-OES spectrometer PerkinElmer Optima 7300 DV, Waltham, Massachusetts, U.S.A.). The exchangeable soil cations were extracted with a 1M ammonium acetate solution and their contents determined by means of an ICP-OES spectrometer (PerkinElmer Optima 7300 DV, Waltham, Massachusetts, U.S.A.), while the total organic C content was determined using the Walkley-Black method (Walkley & Black, 1934). The electrical conductivity of the saturated soil extract (EC_e) was measured to determine the effect of the different irrigation strategies on the salt distribution in the soil below the drip lines. For this purpose, soil samples were collected at 150 mm depth increments below, 300 and 600 mm away from a dripper in each experiment plot. The soil samples where saturated with deionised water at BEMLAB and the EC_e was determined by filling a US Bureau of Soil Standards electrode cup with the saturated paste.

3.2.6 Soil water status

Soil water content (SWC) was measured by means of the neutron scattering technique using a neutron probe (HYDROPROBE 503DR, CPN®, California). A 50 mm Ø class 4 Polyvinyl chloride [IUPAC: Poly(chloroethanediyl)] neutron probe access tube was installed in each experiment plot. A 50 mm Ø custom built tube auger was used to minimize the disturbance of the soil around the access tubes. Soil water content was measured at 200, 300, 600 and 900 mm soil depths, scanning at 8 seconds per depth reading. As it is generally accepted that the neutron scattering technique measures the soil water content of a sphere with a diameter of *ca.* 300 mm (Hillel, 1980), soil water content was measured in 50 mm to 150 mm, 150 mm to 450 mm, 450 mm to 750 mm and 750 mm to 1050 mm soil depth increments. Measurements were carried out once a week during September and October, two times per week during November and three times per week from the beginning of December until harvest in March. The SWC was also measured before and after irrigations. Following harvest, SWC was measured weekly until the first winter rainfall occurred and monthly thereafter.

The neutron probe count ratios, *i.e.* ratio between actual reading at a specific depth and the average of ten standard readings taken while the instrument was standing on the neutron probe box, was calibrated against gravimetric soil water content (P_w) during the first season. Gravimetric soil water content was determined by collecting soil samples at 250 to 350 mm, 550 to 650 mm and 850 to 950 mm soil depths using a Viehmeyer auger on the same days that neutron probe readings were taken. Gravimetric samples were collected into metal cans, sealed and transported back to the Irrigation laboratory at ARC Infruitec-Nietvoorbij. On arrival, the samples were weighed on an electronic balance. The cans were opened and placed in an extractor oven to dry at 105ºC for 24 hours (Hillel, 1980). After the samples were removed from the oven, the cans were closed and placed for an hour in a desiccator containing $CuSO_4$ crystals to allow the tins to cool. Following this, samples were weighed and the P_w determined as percentage water by means of the following equation (Hillel, 1980):

$$P_w\ (\%) = \frac{(\text{Wet sample mass - Dry sample mass})}{\text{Dry sample mass}} \times 100 \qquad (3.2)$$

The volumetric soil water content (θ_v), as mm water per mm soil depth, was determined by using the following equation (Hillel, 1980):

$$\theta_v\ (\text{mm/mm}) = \frac{P_w}{100} \times \frac{\rho_b}{\rho_w} \qquad (3.3)$$

where: θ_v = volumetric soil water content (mm/mm)

P_w = gravimetric soil water content (%)

ρ_b = soil bulk density (kg/m^3)

ρ_w = density of water (kg/m^3)

During the 2005/06 season, Ψ_m was measured by means of Bourdon gauge tensiometers at 300 and 600 mm soil depths, respectively. The relationship between neutron probe count ratios and Ψ_m allowed estimation of Ψ_m beyond the soil water content range where tensiometers cannot function accurately, *i.e.* < -0.08 MPa.

Soil water characteristic curves were determined *in situ* at 300 and 600 mm depths by relating the volumetric soil water content to Ψ_m. Field water capacity and permanent wilting point (PWP) of the soil were estimated as being at -0.01 MPa Ψ_m and -1.50 MPa Ψ_m, respectively (P.A. Myburgh, personal communication, 2006). The soil water characteristic curves was used to calculate soil water holding capacity as the difference in the SWC at FC and at PWP for the 0 to 450 mm and 450 to 750 mm soil layers, respectively. The 0 to 450 mm layer consisted of neutron measurements taken at 200 mm and 300 mm depths and that the probe measured a 300 mm Ø sphere (P.A. Myburgh, personal communication, 2006). Since the majority of the grapevine roots were observed within the 0 to 700 mm soil layer, this was considered the root zone depth. Consequently, SWC was expressed as mm water per 750 mm soil depth. The SWC at 900 mm depth was measured to monitor if any drainage occurred following irrigations. The irrigation volumes applied per solenoid valve on the manifold as discussed in Section 3.2.2, were recorded by means of water meters installed in two replications per depletion level treatment. Irrigation volumes were recorded after each irrigation was applied.

3.2.7 Evapotranspiration and crop coefficients

Crop evapotranspiration (ET_c) was determined as follows using the universal soil water balance equation (Allen *et al.*, 1998):

$$ET_c = \frac{I + P - RO - DP + CR \pm \Delta SF \pm \Delta SW}{t} \tag{3.4}$$

where: ET_c = crop evapotranspiration (mm/day)

I = irrigation applied (mm)

P = rainfall (mm)

RO = run off from surface after irrigation or rain (mm)

DP = deep percolation or drainage out of the root zone (mm)

CR = capillary rise into the root zone (mm)

ΔSF = addition or loss of water due to subsurface flow (mm)

ΔSW = change in soil water content (mm) between consecutive measurements of SWC.

t = time elapsed (days)

The hourly reference evapotranspiration (ET_o) was calculated from the mean air temperature, incoming solar radiation, relative humidity and wind speed values recorded by the automatic weather station near the experiment vineyard. The following modified Penman-Monteith equation was used to calculate the ET_o (Allen *et al.*, 1998):

$$ET_o = \frac{0.408\,\Delta\,(R_n + G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma\,(1 + 0.34 u_2)} \qquad (3.5)$$

where: ET_o = reference evapotranspiration (mm/day)

R_n = net solar radiation at crop surface (MJ/m^2/day)

G = soil heat flux density (MJ/m^2/day)

T = mean daily air temperature at 2 m height (ºC)

u_2 = mean wind speed at 2 m height (m/s)

e_s = saturation vapour pressure (kPa)

e_a = actual vapour pressure (kPa)

$e_s - e_a$ = saturation pressure deficit (kPa)

Δ = slope vapour pressure curve (kPa/ºC)

γ = psychrometric constant (kPa/ºC)

The monthly crop coefficient (K_c) for each of the ten different irrigation treatments during the three seasons was calculated by dividing the ET_c by the ET_o over the same period (Smart & Coombe, 1983; Allen *et al.*, 1998; Myburgh, 2003):

$$K_c = \frac{ET_c}{ET_o} \tag{3.6}$$

3.2.8 Statistical analyses

Raw data were captured and processed using Microsoft® Excel. The latter software was used to calculate the standard deviation from the means. Statgraphics® was used to fit regression models.

3.3 RESULTS AND DISCUSSION

3.3.1 Atmospheric conditions

Mean monthly air temperature, relative humidity, wind, solar radiation and ET_o indicated that the atmospheric conditions varied to some extent during the three seasons, *i.e.* 2006/07 to 2008/09 (Tables 3.2 to 3.4). The variation in seasonal atmospheric conditions could contribute to differences in grapevine irrigation requirements between seasons. Typical for South Africa, seasonal rainfall was erratic and not comparable to the long-term mean values for two of the seasons. In the 2006/07, 2007/08 and 2008/09 seasons 69 mm, 212 mm and 183 mm rainfall, respectively, occurred from bud break in September until harvest in March (Table 3.4).

3.3.2 Soil description and classification

The soil in the experiment vineyard was classified as a Valsrivier soil form (Soil Classification Working Group, 1991) or Cutanic Luvisol (IUSS Working Group WRB, 2001; Fey, 2010), with an orthic A horizon and pedocutanic B horizon overlying a horizon consisting of unconsolidated material without signs of wetness. The orthic A horizon was bleached and had a 7.5 YR 8/6 and 2.5 YR 4/8 colour in its dry and moist conditions, respectively, according to the Munsell standard soil colour chart (Anonymous, 1970). The pedocutanic B horizon colour was 2.5 YR 4/8 in both dry and moist state and had a sub-angular structure. Free lime mottles did not occur in the pedocutanic B horizon of all the experiment plots and the plots therefore were

Table 3.2 The long term mean (LTM) values, as well as the monthly mean daily maximum (T_x), minimum (T_n) and average (T_{ave}) temperatures during three seasons near Robertson.

Month	T_x (ºC)				T_n (ºC)				T_{ave} (ºC)			
	LTM	2006/07	2007/08	2008/09	LTM	2006/07	2007/08	2008/09	LTM	2006/07	2007/08	2008/09
April	23.6	25.2	26.3	26.1	10.2	11.6	11.8	10.9	16.3	18.1	18.6	18.0
May	20.3	20.7	23.3	23.0	7.4	8.1	8.9	11.0	13.6	13.8	15.4	16.7
June	18.0	21.0	23.6	18.9	4.7	6.1	8.4	7.8	10.7	12.7	15.3	13.3
July	17.9	19.5	18.7	18.3	3.8	6.6	4.6	5.1	10.2	12.6	11.0	11.2
August	18.4	18.7	19.3	19.3	5.2	7.2	6.0	6.2	11.3	12.6	12.3	12.5
September	21.1	22.3	22.9	19.6	7.4	9.6	8.1	6.3	13.5	15.6	15.2	13.0
October	24.0	24.8	25.1	25.0	9.5	10.7	10.7	11.0	16.2	17.6	17.6	17.4
November	26.1	27.2	25.6	26.3	11.7	13.6	12.6	13.6	18.1	20.1	18.7	19.5
December	27.2	28.4	29.0	29.7	13.5	15.1	16.1	15.6	19.7	21.4	22.1	22.1
January	28.5	32.6	30.3	29.4	14.3	17.2	17.1	16.4	20.1	24.2	23.0	22.4
February	29.6	30.5	30.5	30.8	15.0	16.1	17.2	16.8	21.1	22.7	23.3	23.2
March	26.3	28.9	29.6	31.0	12.8	13.7	14.7	15.3	19.3	21.1	21.6	22.4

Table 3.3 The long term mean (LTM) values, as well as the monthly mean daily maximum (RH_x) and minimum (RH_n) relative humidity and mean reference evapotranspiration (ET_o) during three seasons near Robertson.

Month	RH_x (%)				RH_n (%)				ET_o[1] (mm/day)			
	LTM	**2006/07**	**2007/08**	**2008/09**	**LTM**	**2006/07**	**2007/08**	**2008/09**	**LTM**	**2006/07**	**2007/08**	**2008/09**
April	*79.2*	90.5	88.1	87.8	*33.8*	42.2	31.1	31.2	*2.96*	4.01	3.93	4.02
May	*79.9*	89.7	91.1	88.3	*38.3*	43.5	35.7	37.0	*2.15*	2.20	2.35	3.05
June	*81.7*	87.6	91.3	89.4	*40.5*	40.5	40.5	42.1	*1.85*	2.56	2.89	2.44
July	*81.3*	89.1	93.1	91.8	*37.0*	46.4	36.5	40.9	*2.01*	2.42	1.48	2.63
August	*80.4*	92.8	91.2	91.6	*38.2*	43.4	37.0	37.4	*2.37*	1.77	3.39	2.97
September	*76.2*	93.1	90.1	90.0	*31.3*	40.6	30.7	31.9	*3.35*	3.92	5.17	4.24
October	*72.9*	90.9	88.0	86.8	*29.7*	34.7	33.2	32.5	*4.51*	5.68	5.04	5.88
November	*72.8*	85.9	83.9	86.2	*29.9*	31.5	30.4	36.4	*5.41*	7.07	6.61	6.72
December	*70.4*	81.5	87.1	83.7	*28.1*	28.4	35.8	28.8	*5.99*	7.85	7.27	7.61
January	*73.8*	81.8	84.3	82.0	*29.0*	25.4	33.7	30.8	*5.85*	8.27	7.65	7.07
February	*74.3*	85.9	85.9	82.2	*30.2*	30.2	33.3	29.0	*5.47*	7.40	6.85	7.35
March	*76.2*	85.7	86.7	83.4	*29.7*	28.3	30.5	27.0	*4.38*	6.27	5.83	5.77

[1] ET_o determined using a modified Penman-Monteith equation.

Table 3.4 The long term mean (LTM) values, as well as the monthly mean daily incoming solar radiation (R_s) and wind (U_2) and mean monthly rain during three seasons near Robertson.

Month	Incoming solar radiation (MJ/m^2/day)				Wind (m/s)				Rain(mm)			
	LTM	2006/07	2007/08	2008/09	LTM	2006/07	2007/08	2008/09	LTM	2006/07	2007/08	2008/09
April	*12.2*	15.6	16.8	17.0	*1.7*	2.0	1.8	1.7	*35*	5	16	6
May	*8.9*	11.2	12.4	11.8	*1.8*	1.7	1.7	2.0	*27*	48	34	22
June	*8.4*	10.7	13.8	9.2	*1.8*	1.7	2.2	2.3	*19*	12	32	13
July	*9.2*	10.0	12.1	11.4	*1.9*	2.0	2.2	2.1	*33*	69	65	90
August	*11.3*	13.0	14.4	15.4	*2.3*	2.3	2.3	2.4	*38*	93	25	63
September	*15.3*	17.5	20.7	20.9	*2.5*	2.0	2.3	2.8	*10*	8	7	42
October	*19.5*	22.4	24.7	25.8	*2.4*	2.1	2.2	2.4	*24*	19	29	12
November	*23.5*	28.0	26.9	28.1	*2.5*	2.4	2.3	2.3	*28*	17	90	100
December	*24.4*	29.3	29.4	30.2	*2.5*	2.5	2.3	2.1	*29*	4	33	19
January	*24.6*	31.4	30.2	28.4	*2.5*	2.4	2.4	2.1	*19*	0	2	0
February	*21.9*	27.3	27.5	27.0	*2.5*	2.3	2.2	2.4	*8*	20	46	9
March	*17.4*	23.3	22.4	22.7	*2.0*	2.0	2.0	1.9	*15*	1	5	1
Total									285	296	384	377

either part of the Alice soil family (no free lime present in the B horizon) or the Keiskamma soil family (free lime present in the B horizon) (Soil Classification Working Group, 1991). The clay contents estimated in the field were approximately 15% and the sand grade predominantly fine sand.

3.3.3 Soil physical properties

According to the soil particle distribution, the 0 to 300 mm and 300 to 700 mm depth soil layers had a fine sandy loam texture (Table 3.5). Soil texture was reasonably homogenous across the experiment vineyard. The mean ρ_b was 1517 kg/m^3 and 1526 kg/m^3 for the 0 to 300 mm and 300 to 700 mm soil layers, respectively, which indicated that no excessive soil compaction occurred in the root zones (Van Huyssteen, 1981, Van Huyssteen, 1983).

3.3.4 Soil chemical status

Chemical status of the soil indicated that problems regarding root growth and functioning or nutrient deficiencies were not to be expected (Table 3.6) (Saayman, 1981). The sodium adsorption ratio (SAR) for the 0 to 300 mm and 300 to 700 mm soil layers was 0.07 and 0.14, respectively, and no sodicity hazards occurred in the soil (Van Zyl, 1981). After the completion of the trial, it was found that the different irrigation strategies had no significant effect on the mean EC_e distribution throughout the soil profiles (Figure 3.6 to 3.8). No salinity problems occurred in any of the plots (Saayman, 1981).

3.3.5 Soil water content

The soil water characteristic curves, non-linear regression equations and correlation coefficients for the 0 to 450 mm and 450 to 750 mm soil layers are presented in Figures 3.9 and 3.10, respectively. The water holding capacity in the 0 to 450 mm soil layer was *ca.* 0.127 mm/mm, compared to *ca.* 0.122 mm/mm in the 450 to 750 mm layer. Although the deeper soil layer had a higher clay content, it also had a higher coarse sand and lower fine sand content than the top soil layer (Table 3.5). Hall *et al.* (1977) indicated that clay release very little water in the 0.05 to 0.4 bar soil matric potential range, while fine sands will release larger amounts more readily at the mentioned matric potential range. The total soil water holding capacity for the root zone depth was 93.68 mm/750 mm or 0.1249 mm/mm. Field capacity and PWP

Table 3.5 The mean particle size distribution, sand grade, soil textural class and bulk density in the soil where the field trial was carried out near Robertson.

Soil depth (mm)	Clay (%)	Silt (%)	Fine sand (%)	Medium sand (%)	Coarse sand (%)	Sand grade	Soil texture class	Soil bulk density (kg/m^3)
0-300	13.5±3.3	6.0±1.5	65.3±6.7	12.2±6.2	3.0±1.8	Fine	Sandy loam	1517±84.7
300-700	18.8±7.6	5.3±1.8	59.4±7.8	11.4±5.5	5.1±6.0	Fine	Sandy loam	1526±50.7

Table 3.6 The mean soil chemical status of the fine sandy loam soil in which the field trial was carried out near Robertson at the completion of the trial.

Soil depth	$pH_{(KCl)}$	EC_e	Bray II ($mg.kg^{-1}$)		Exchangeable cations (cmol(+)/kg)				Organic C
(mm)		($dS.m^{-1}$)	P	K	Na	K	Ca	Mg	(%)
0-300	7.2±0.5	0.20±0.09	8.4±5.7	300.3±70.4	0.2±0.1	0.8±0.2	11.5±5.3	2.9±0.5	0.5±0.2
300-700	7.3±0.5	0.20±0.09	3.4±2.4	209.5±65.3	0.4±0.1	0.5±0.2	12.2±5.6	4.1±1.1	0.2±0.1

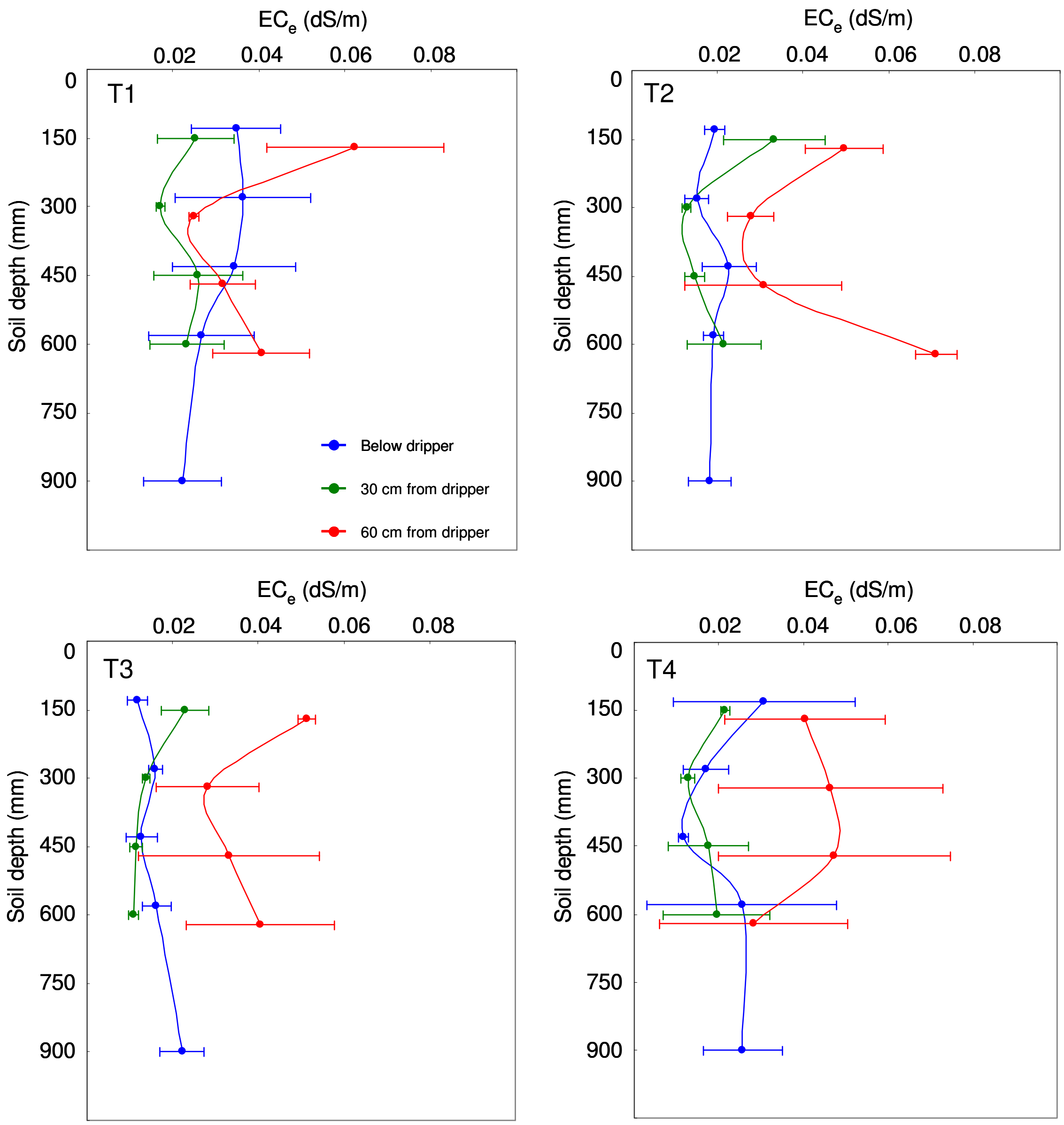

Figure 3.6 Effect of different irrigation strategies (T1, T2, T3 & T4) on the soil Electrical Conductivity (EC_e) around the drippers in a fine sandy loam soil near Robertson. Horizontal bars indicate the standard deviation of the three replications. (Refer to Table 3.1 for description of strategies).

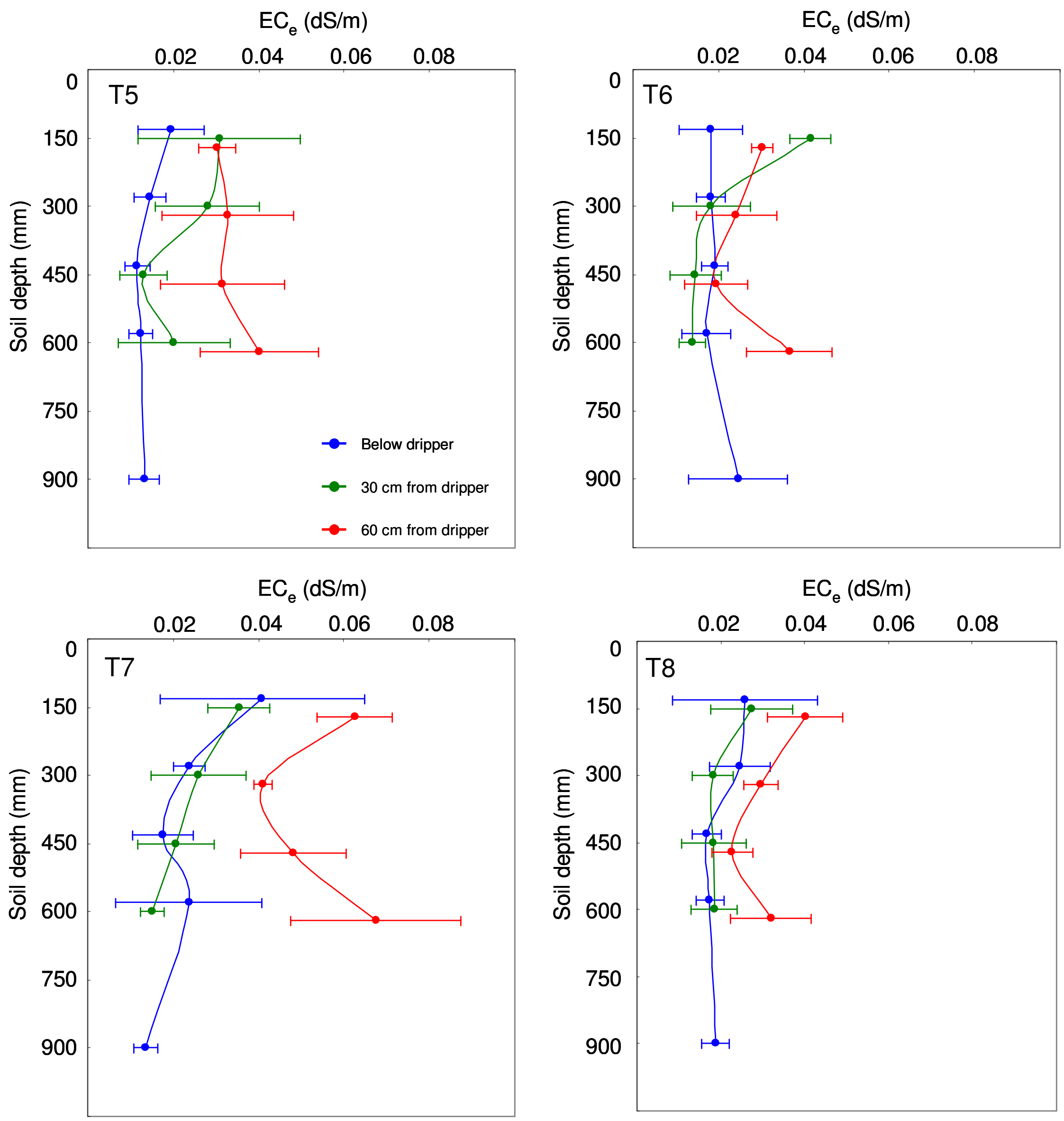

Figure 3.7 Effect of different irrigation strategies (T5, T6, T7 & T8) on the Electrical Conductivity (EC$_e$) around the drippers in a fine sandy loam soil near Robertson. Horizontal bars indicate the standard deviation of the three replications. (Refer to Table 3.1 for description of strategies).

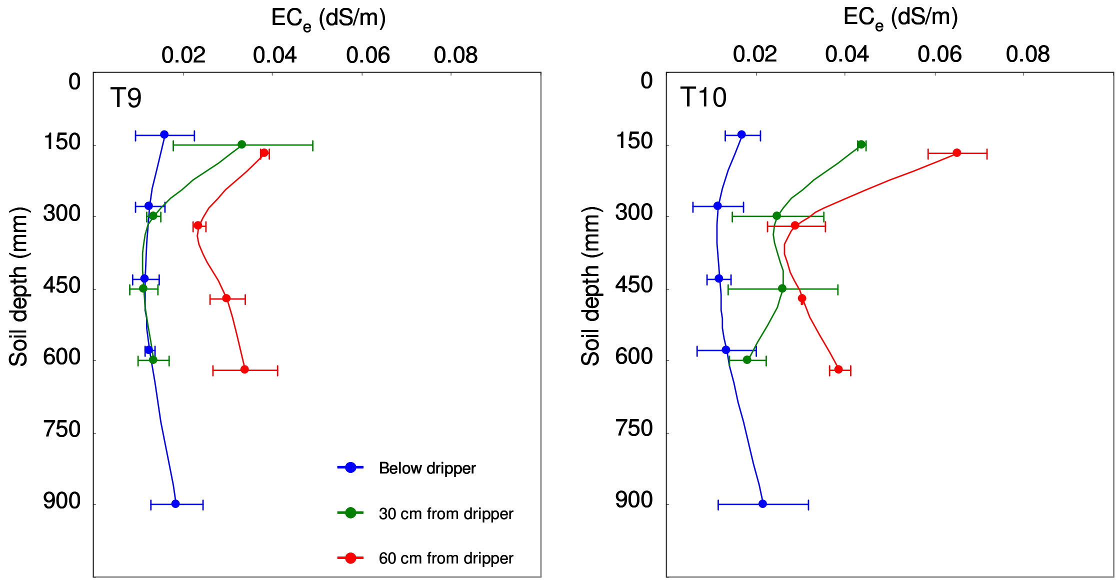

Figure 3.8 Effect of different irrigation strategies (T9 & T10) on the Electrical Conductivity (EC_e) around the drippers in a fine sandy loam soil near Robertson. Horizontal bars indicate the standard deviation of the three replications. (Refer to Table 3.1 for description of strategies).

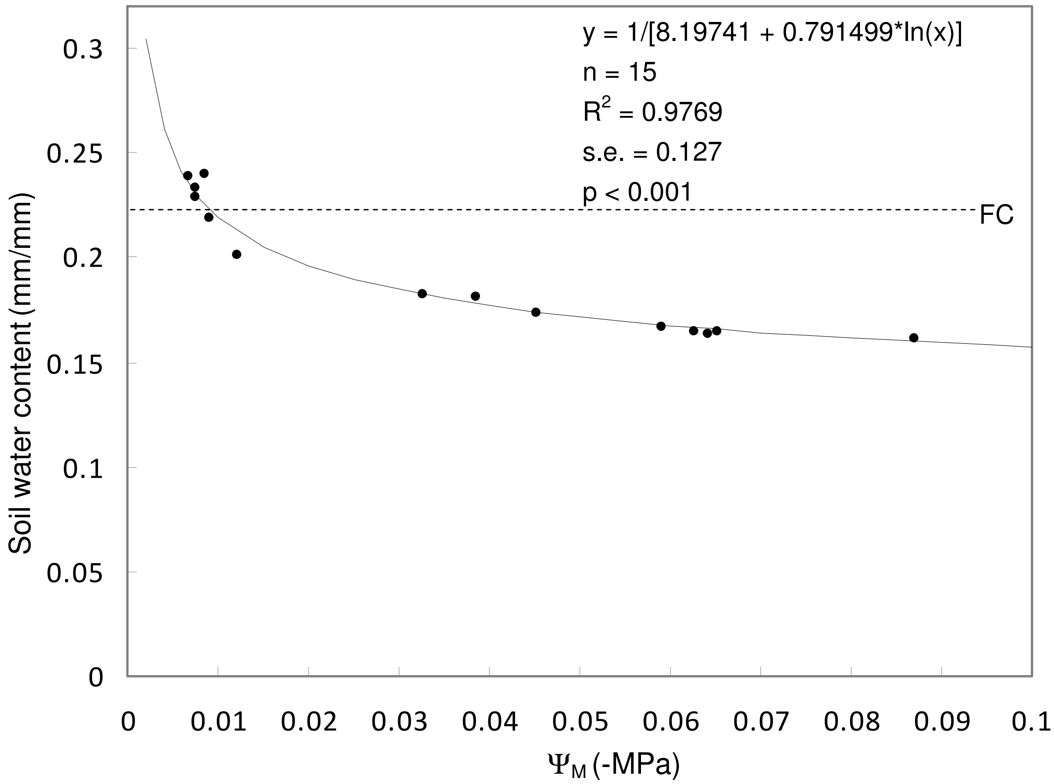

Figure 3.9 Estimated soil water characteristic curve for the 0 to 450 mm soil layer of a fine sandy loam soil near Robertson. Field capacity is indicated by FC.

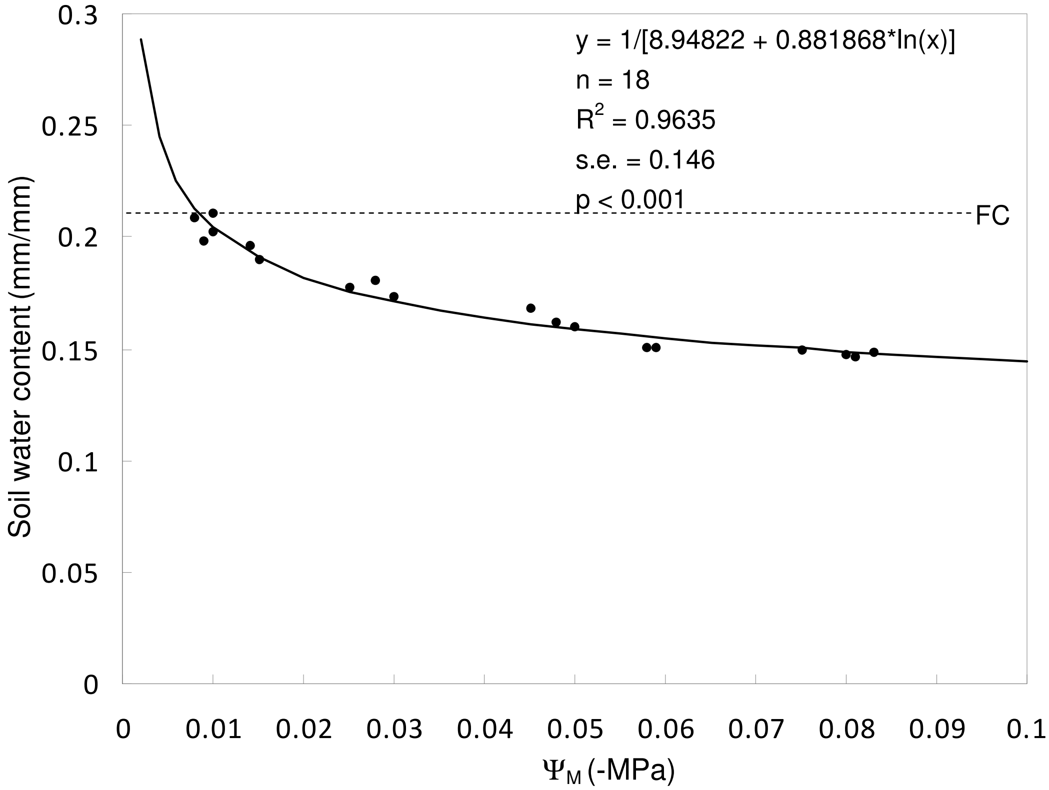

Figure 3.10 Estimated soil water characteristic curve for the 450 mm to 750 mm soil layer of a fine sandy loam soil near Robertson. Field capacity is indicated by FC.

amounted to 165.33 mm/750 mm and 71.65 mm/750 mm, respectively.

Except for the 2006/07 season, soil water content (θ_v) in the root zones of all the experiment plots was refilled to FC before bud break in the beginning of September. The seasonal variation in θ_v for the 2008/09 season is presented in Figures 3.11 to 3.20. Variation in θ_v for the treatments was comparable between the three seasons (data not shown). In order to maintain 30% to 40% PAW depletion levels over the entire season (T1), as well as during the post-véraison period (T2 & T5), grapevines had to be irrigated twice per week (*ca.* six hours per irrigation) from mid October until the beginning of December and three times per week from the beginning of December until harvest in March. In the case of the CDI strategy, grapevines had to be irrigated two times per week (*ca.* three hours per irrigation) from mid October. The grapevines of the CDI treatments (T8 & T9) absorbed water primarily from the 0 to 450 mm soil layer between flowering and the pea size phenological stage. During this period only small amounts of water were absorbed from the 450 mm to 750 mm layer (data not shown). As the soil progressively dried out more water was absorbed from the deeper soil layer from the beginning of December. From the second week in November, irrigations were applied approximately every 14 days to 21 days to maintain the 70% to 80% PAW depletion required for the T2, T3 and T4 strategies. In the case of 90% PAW depletion, grapevines of the T5, T6 and T7 strategies received their first irrigations in early and mid December respectively during the first two seasons and a second one in mid January (at *ca.* 100% véraison). One more irrigation of 20 hours was necessary during these seasons to maintain a PAW depletion of 90% or higher. During the 2008/09 season, 110 mm rainfall in the middle of November resulted in the 90% depletion level treatments receiving only a single irrigation during mid January 2009. For the partial profile refill (PPR) strategy (T10), *i.e*. where PAW depletion was maintained between 40% and 60% during the post-véraison stage, grapevines had to be irrigated two times per week (*ca.* four hours per irrigation) until harvest. During the ripening stage, T8 grapevines had to be irrigated four times (3 hours) in order to keep the PAW depletion level constant and to keep the grapevines alive since the θ_v in these plots exceeded 90% PAW depletion during this particular phase.

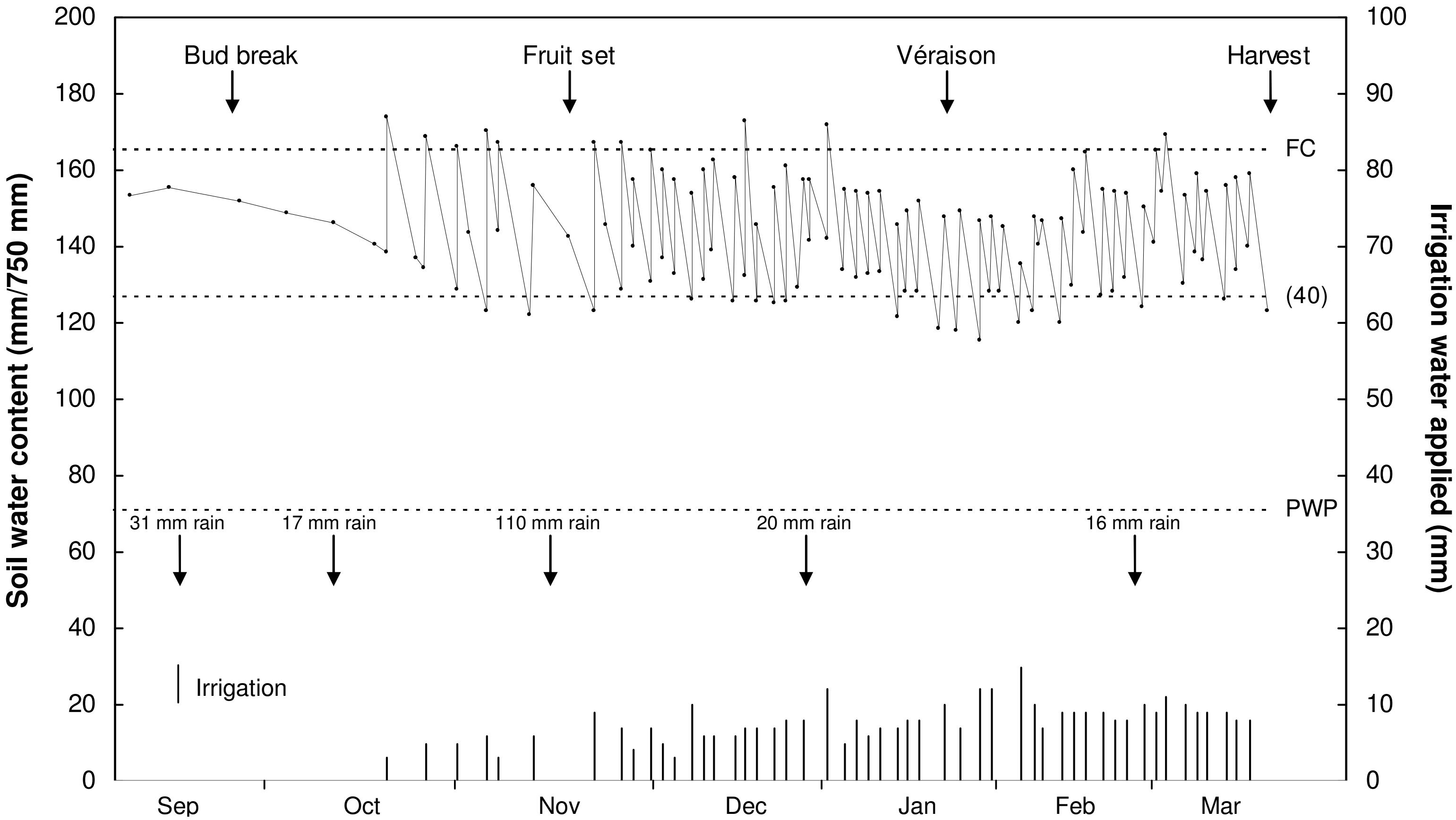

Figure 3.11 Variation in soil water content where Shiraz/110R in a fine sandy loam soil was irrigated at 30% to 40% plant available water (PAW) depletion until harvest (T1) during the 2008/09 season near Robertson. FC and PWP are field capacity and permanent wilting point, respectively, whereas values in brackets designate PAW depletion levels.

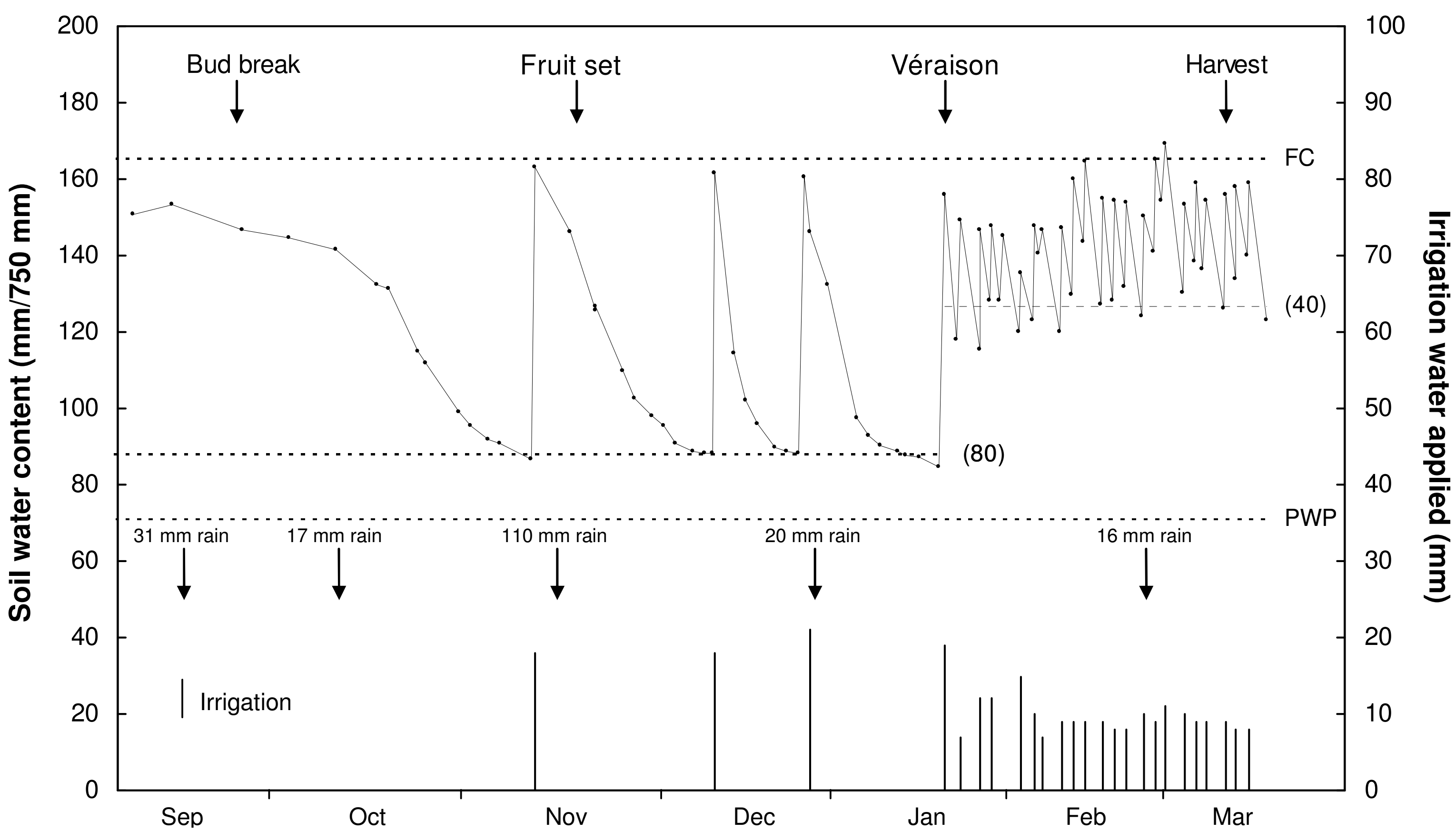

Figure 3.12 Variation in soil water content where Shiraz/110R in a fine sandy loam soil was irrigated at 70% to 80% plant available water (PAW) depletion before véraison followed by irrigation at 30% to 40% PAW depletion during ripening (T2) in the 2008/09 season near Robertson. FC and PWP are field capacity and permanent wilting point, respectively, whereas values in brackets designate PAW depletion levels.

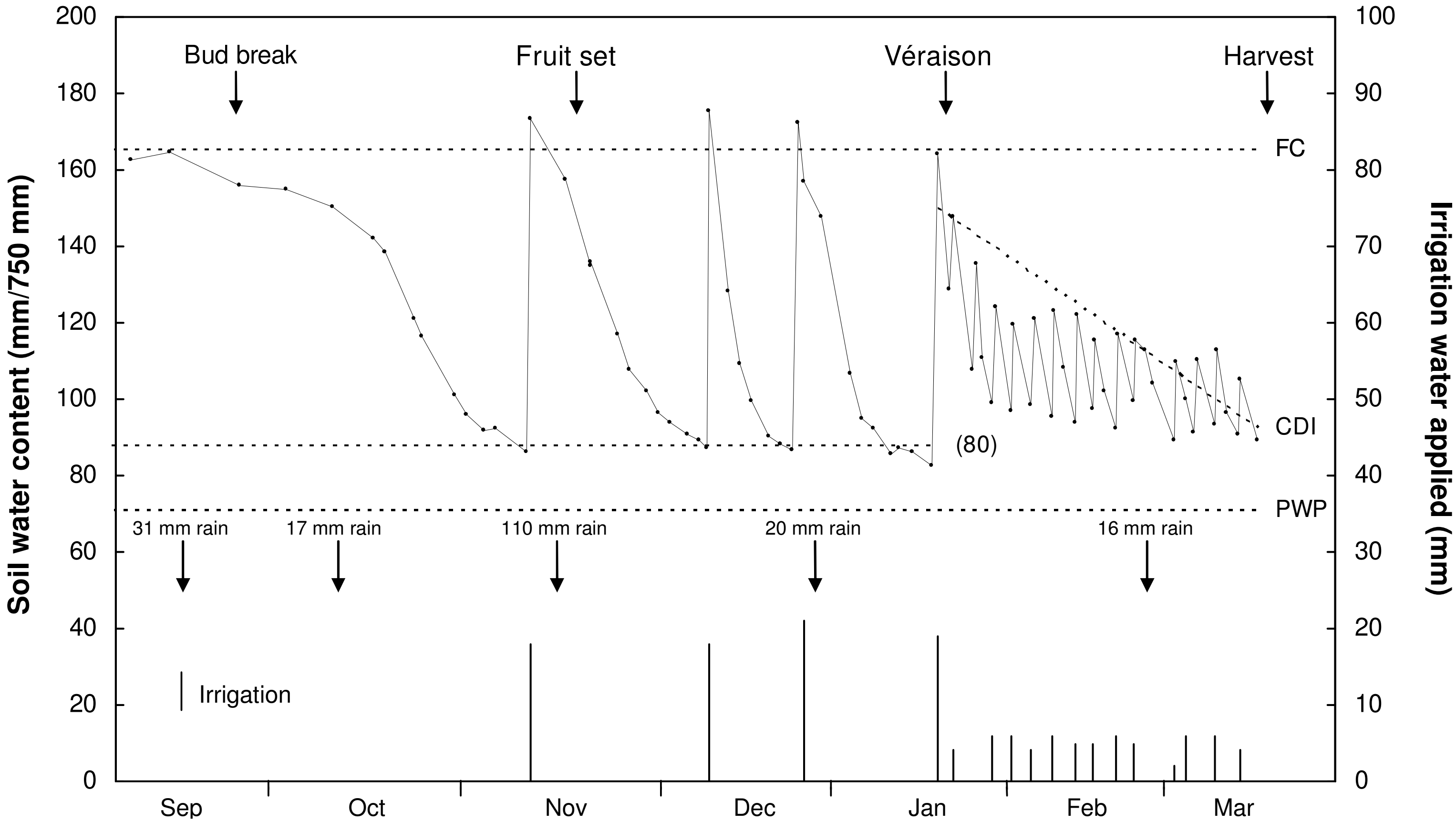

Figure 3.13 Variation in soil water content where Shiraz/110R in a fine sandy loam soil was irrigated at 70% to 80% plant available water (PAW) depletion before véraison followed by a continuous deficit irrigation (CDI) strategy during ripening (T3) in the 2008/09 season near Robertson. FC and PWP are field capacity and permanent wilting point, respectively, whereas values in brackets designate PAW depletion levels.

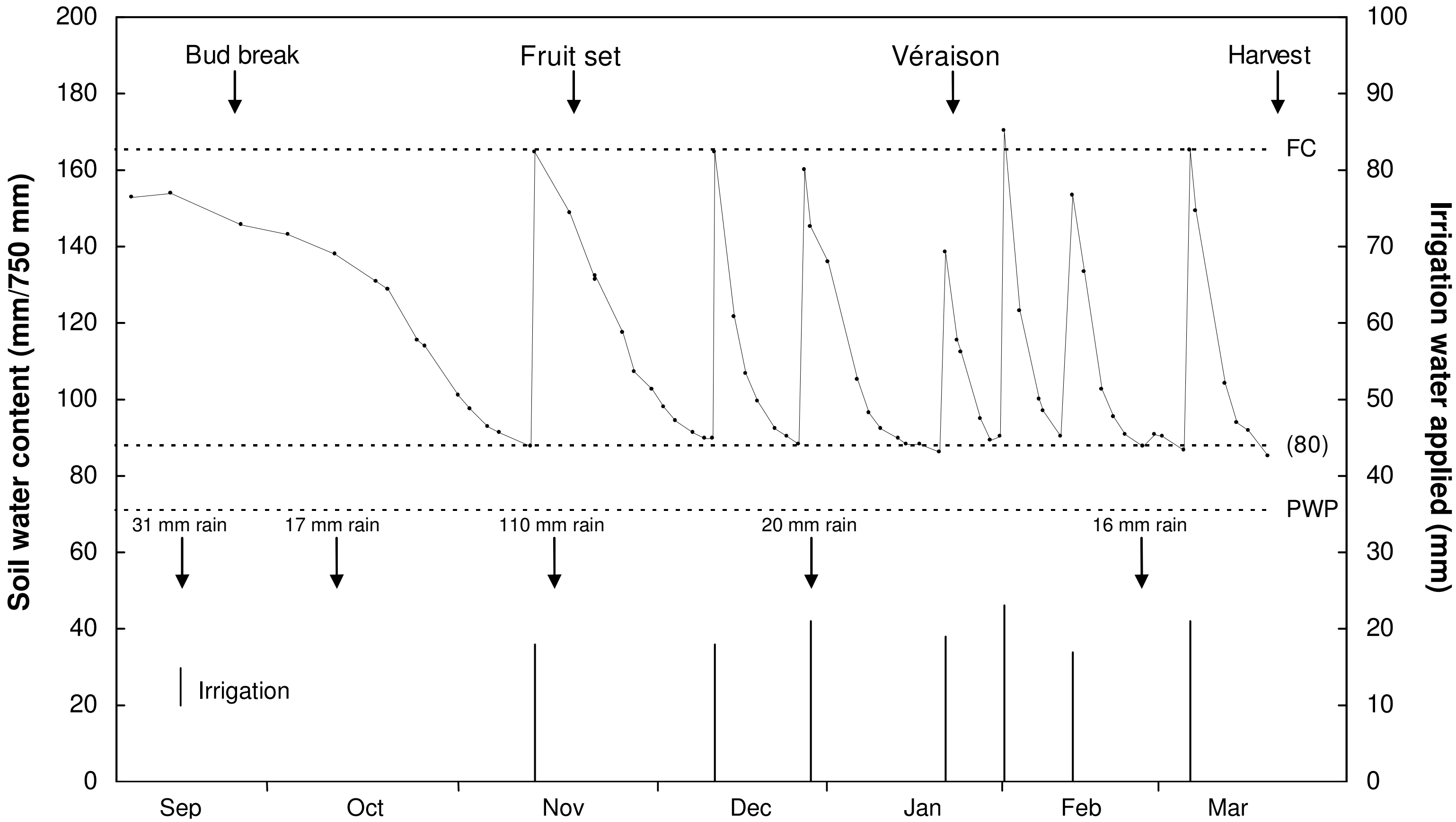

Figure 3.14 Variation in soil water content where Shiraz/110R in a fine sandy loam soil was irrigated at 70% to 80% plant available water (PAW) depletion until harvest (T4) during the 2008/09 season near Robertson. FC and PWP are field capacity and permanent wilting point, respectively, whereas values in brackets designate PAW depletion levels.

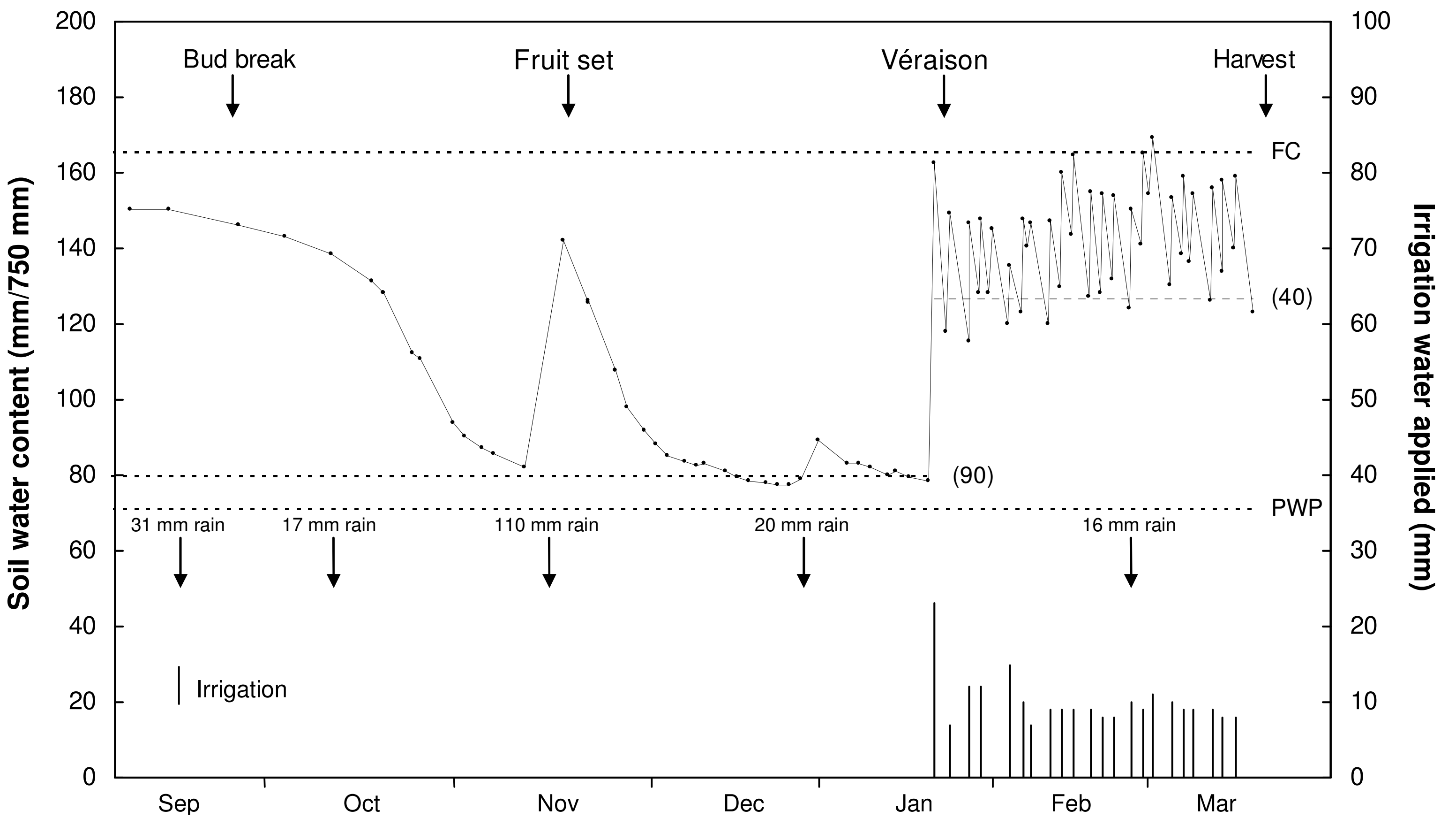

Figure 3.15 Variation in soil water content where Shiraz/110R in a fine sandy loam soil was irrigated at *ca*. 90% plant available water (PAW) depletion before véraison followed by irrigation at 30% to 40% PAW depletion during ripening (T5) in the 2008/09 season near Robertson. FC and PWP are field capacity and permanent wilting point, respectively, whereas values in brackets designate PAW depletion levels.

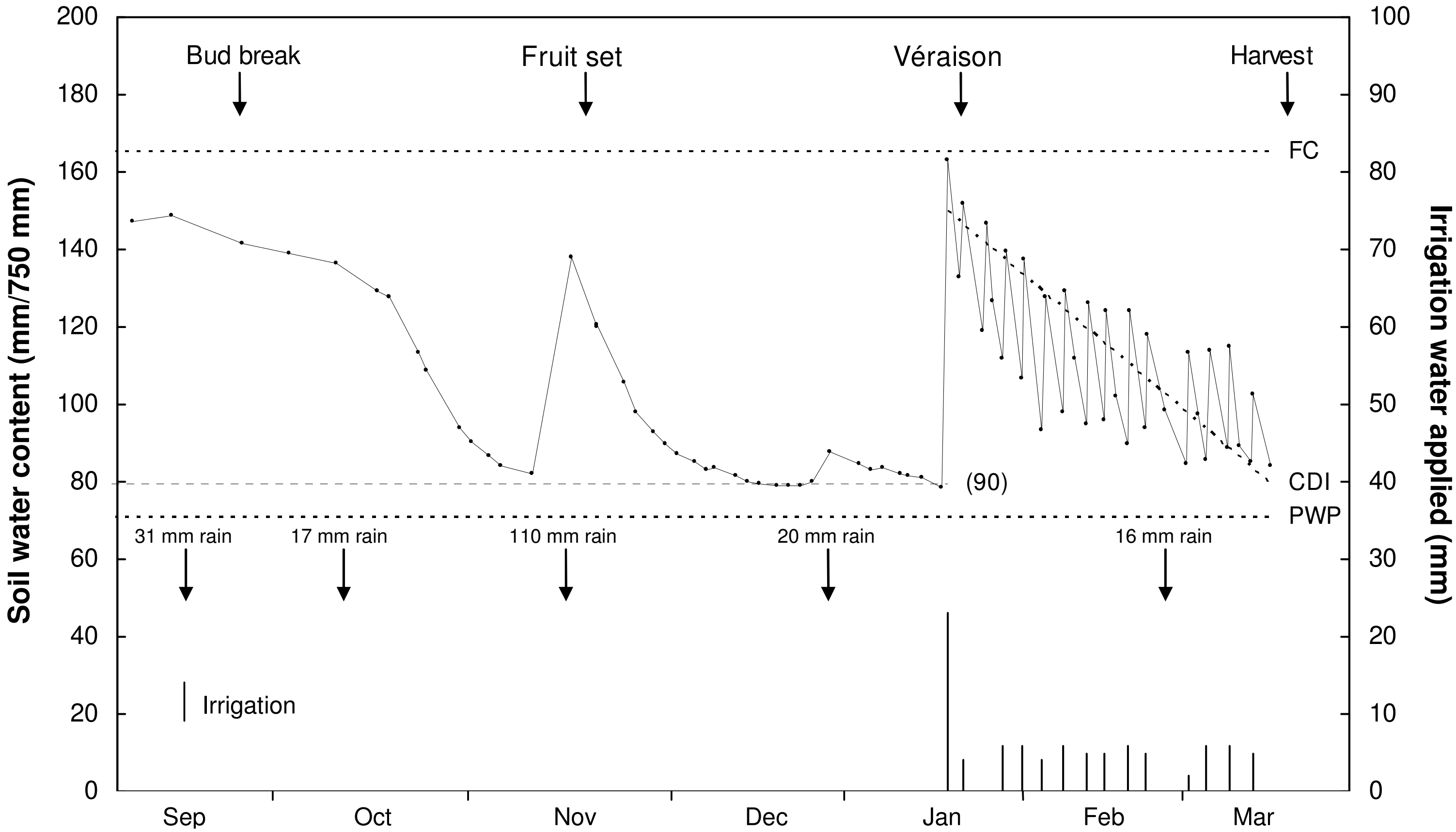

Figure 3.16 Variation in soil water content where Shiraz/110R in a fine sandy loam soil was irrigated at *ca.* 90% plant available water (PAW) depletion before véraison followed by a continuous deficit irrigation (CDI) strategy during ripening (T6) in the 2008/09 season near Robertson. FC and PWP are field capacity and permanent wilting point, respectively, whereas values in brackets designate PAW depletion levels.

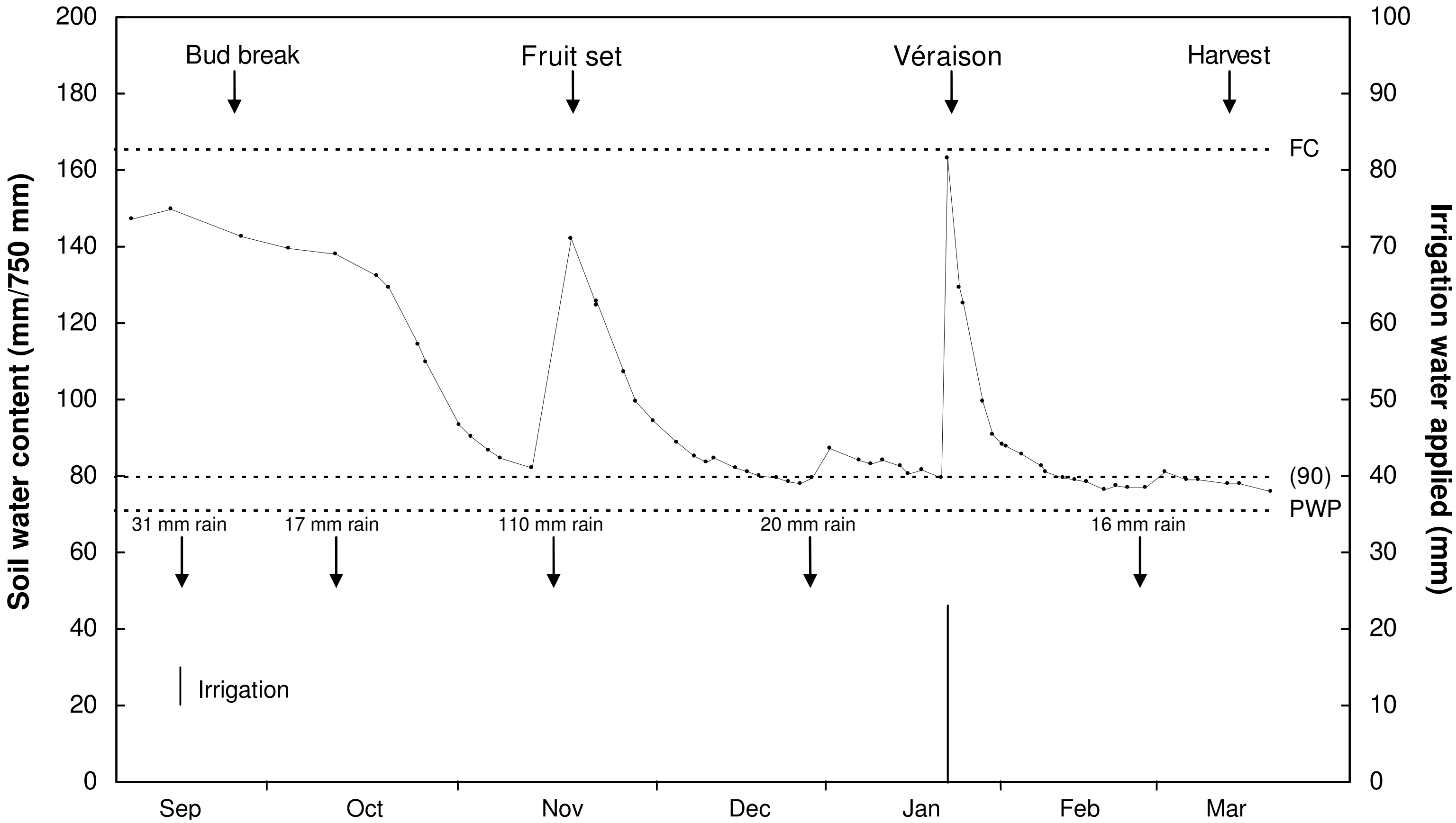

Figure 3.17 Variation in soil water content where Shiraz/110R in a fine sandy loam soil was irrigated at *ca*. 90% plant available water (PAW) depletion until harvest (T7) during the 2008/09 season near Robertson. FC and PWP are field capacity and permanent wilting point, respectively, whereas values in brackets designate PAW depletion levels.

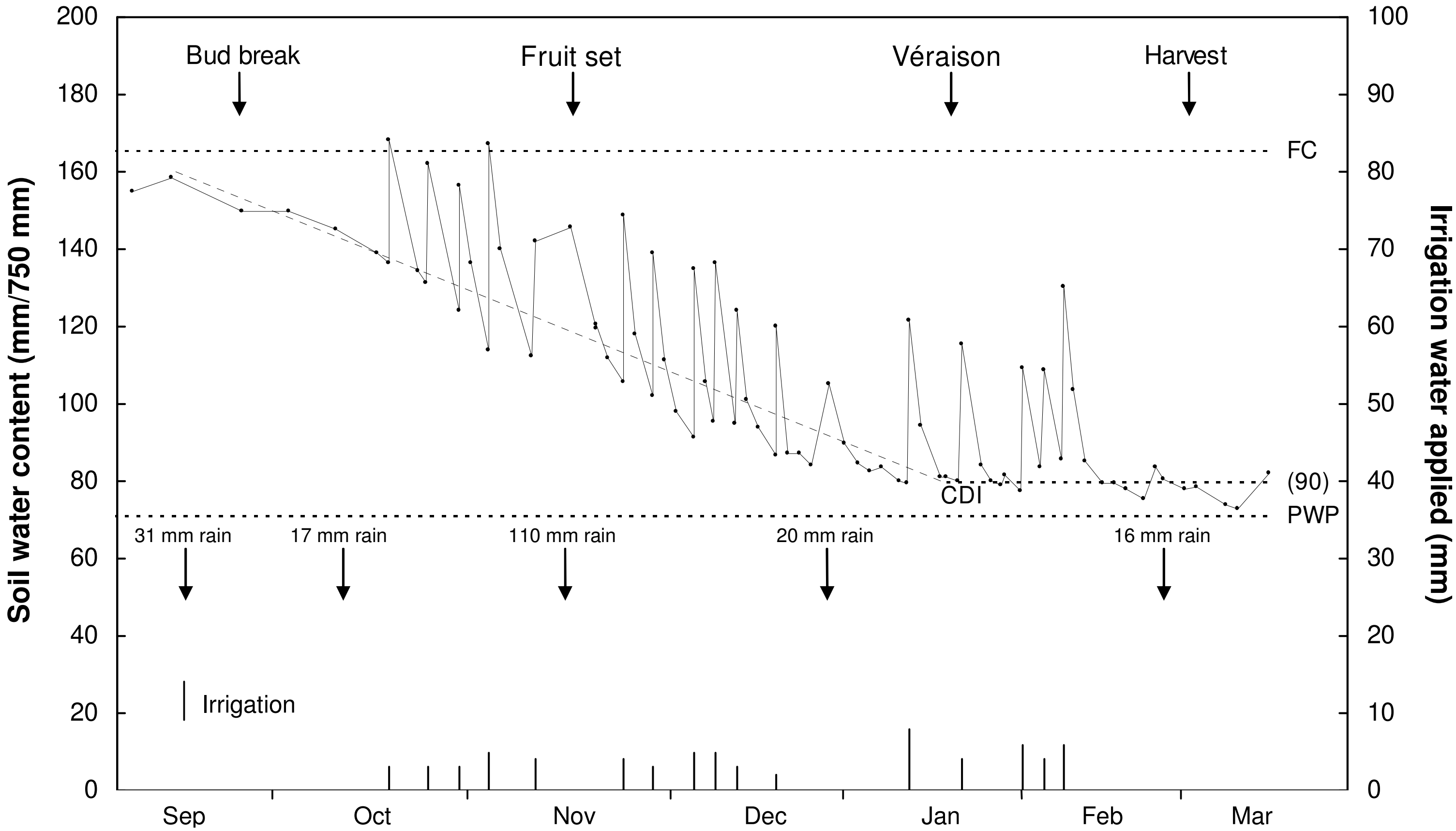

Figure 3.18 Variation in soil water content where Shiraz/110R in a fine sandy loam soil was irrigated according to a continuous deficit irrigation (CDI) strategy until harvest (T8) during the 2008/09 season near Robertson. FC and PWP are field capacity and permanent wilting point, respectively, whereas values in brackets designate plant available water depletion levels.

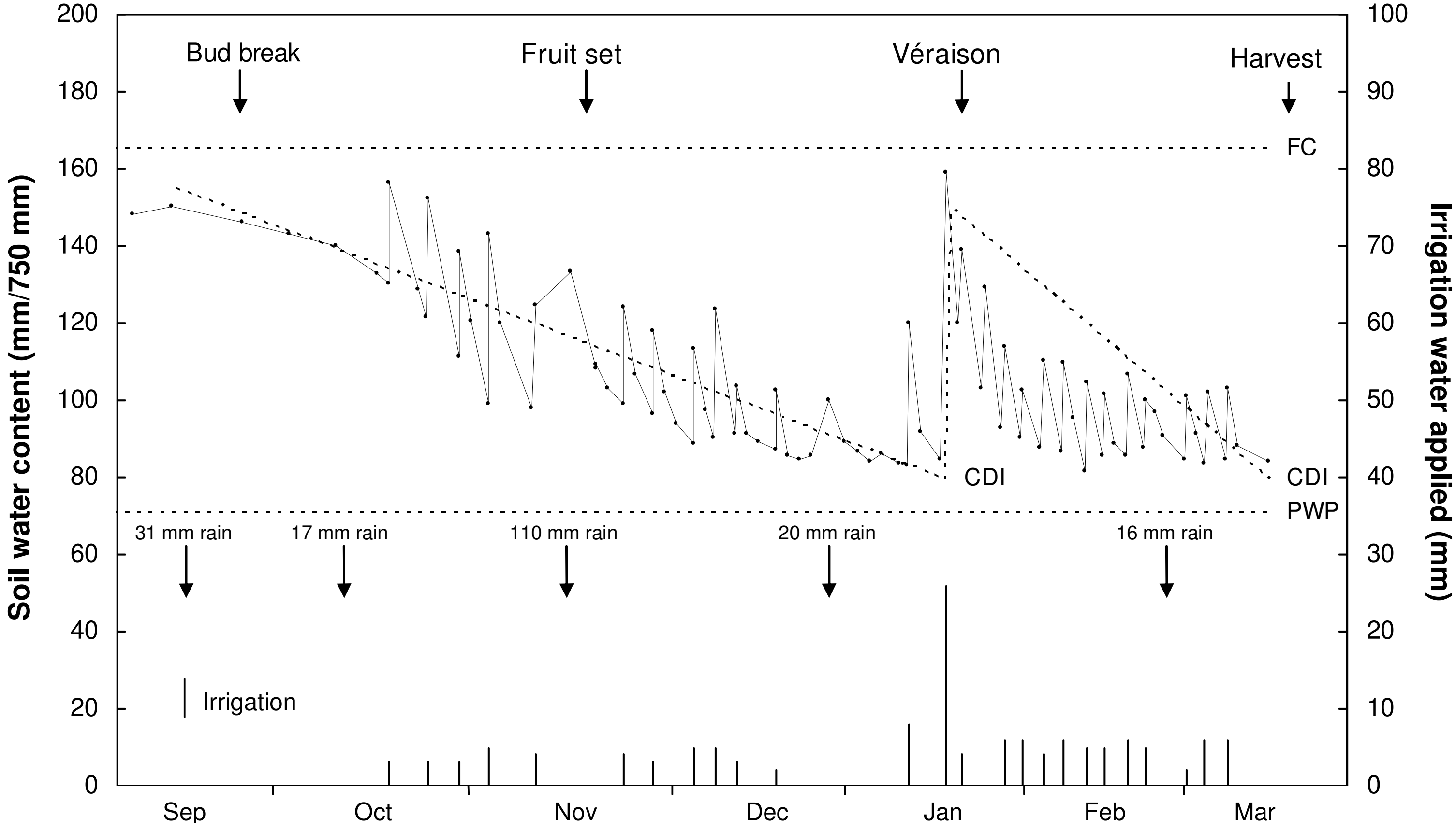

Figure 3.19 Variation in soil water content where Shiraz/110R in a fine sandy loam soil was irrigated according to a continuous deficit irrigation strategy, which included the refilling of the profile at véraison (T9) during the 2008/09 season near Robertson. FC and PWP are field capacity and permanent wilting point, respectively.

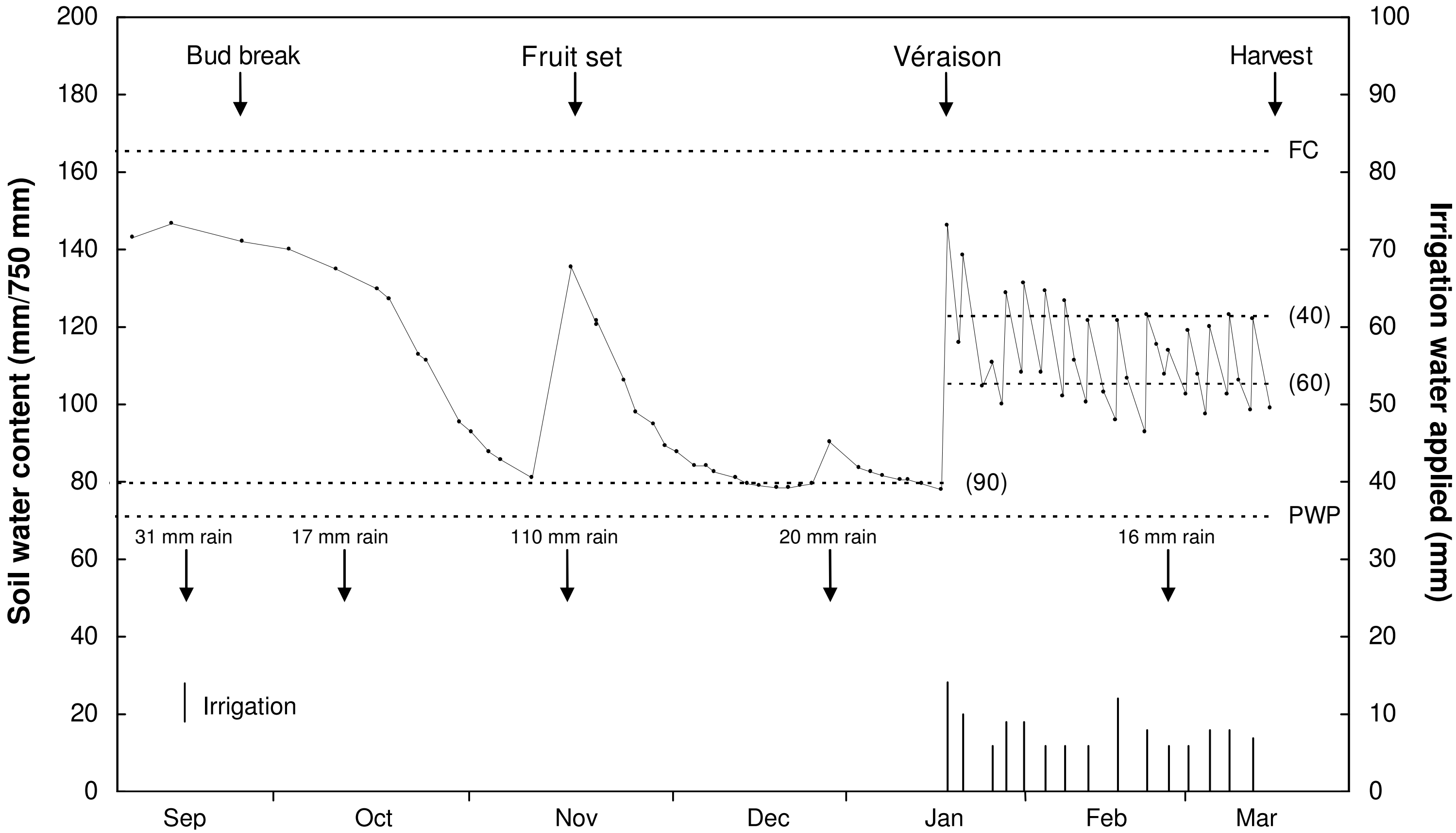

Figure 3.20 Variation in soil water content where Shiraz/110R in a fine sandy loam soil was irrigated at *ca*. 90% plant available water (PAW) depletion before véraison followed by a partial profile refill irrigation strategy during ripening (T10) in the 2008/09 season near Robertson. FC and PWP are field capacity and permanent wilting point, respectively, whereas values in brackets designate PAW depletion levels.

The monthly and total irrigation amounts required (in mm) to maintain the PAW depletion levels during the respective seasons are presented in Tables 3.7 to 3.9. Grapevines of the T2 and T5 strategies received *ca.* 60% of the irrigation amount that was applied to the wettest treatment (T1), whereas those of the T3, T4, T9 and T10 strategies received approximately a third of the irrigation water that was applied to T1. Only 9% and 19% of the irrigated amount applied to the grapevines of T1 were applied to the T7 and T8 grapevines, respectively. The irrigation volumes of the T1 grapevines were similar to the volumes applied to Colombar that was drip irrigated two to three times per week near Robertson (Van Zyl, 1984). However, T1 grapevines received 15% less irrigation water compared to drip irrigated Sultanina grapevines in the Lower Orange River region (Myburgh, 2007). Pinotage and Sauvignon blanc grapevines irrigated by means of micro-sprinklers, and subjected to 50% or 75% RAW depletion, required two and four times more irrigation, respectively, to maintain the depletion levels under similar soil and climatic conditions near Robertson (Myburgh, 2011).

3.3.6 Evapotranspiration and crop coefficients

During the three growing seasons, no drainage, capillary rise, run off or subsurface flow were observed and assumed to be zero. Therefore, only I, P and ΔSW was used to calculate ET_c values. Thus, ET was calculated as follows:

$$ET_c = \frac{I + P \pm \Delta SW}{t} \tag{3.7}$$

The mean daily ET_c per month for the three year period of the field experiment are presented in Tables 3.10 to 3.12. In the 2006/07 and 2008/09 seasons, peak daily ET_c of T1 grapevines, exceeding 3 mm/day, were measured from December to February. The lowest for December was in 2007 when the mean monthly ET_c was 2.36 mm/day and hardly exceeded 3 mm/day during January and February in 2008. This was probably caused by the higher relative humidity that occurred during these months compared to January and February in the other two seasons (Allen *et al.*, 1998). The ET_c of T2 and T5 grapevines were lower than that of the T1 during the ripening phase, even though they were irrigated as frequently and with the same volumes of water as the grapevines of T1. Visually smaller canopies of T2 and T5 grapevines in comparison to T1 grapevine canopies during the post-véraison phase

Table 3.7 The monthly irrigation amounts applied to ten different irrigation treatments on a sandy loam soil near Robertson form April 2006 until March 2007.

	Treatment number									
	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
	Plant available water depletion pre-véraison → post-véraison									
	35%→35%	75%→35%	75%→CDI[1]	75%→75%	90%→35%	90%→CDI	90%→90%	CDI	CDI→CDI	90%→PPR[2]
Month	Irrigation amounts (mm)									
April	0	0	0	0	0	0	0	0	0	0
May	0	0	0	0	0	0	0	0	0	0
June	0	0	0	0	0	0	0	0	0	0
July	0	0	0	0	0	0	0	0	0	0
August	0	0	0	0	0	0	0	0	0	0
September	0	0	0	0	0	0	0	0	0	0
October	14	0	0	0	0	0	0	5	5	0
November	65	24	24	24	0	0	0	24	24	0
December	121	41	41	41	24	24	24	20	20	29
January	116	106	70	54	86	77	73	32	70	43
February	104	104	20	55	104	20	0	20	20	39
March[3]	62	62	3	0	12	3	0	3	3	2
Total	482	337	158	174	226	124	97	104	142	113

[1] Continuous deficit irrigation where grapevines were irrigated frequently, but with low volumes of water to allow the soil to dry out gradually.
[2] Partial profile refill where the soil profile was only refilled partially during irrigations to maintain the plant available water between 40% and 60% depletion.
[3] March irrigation values is only for irrigation until grapes were harvest.

Table 3.8 The monthly irrigation amounts applied to ten different irrigation treatments in a sandy loam soil near Robertson form April 2007 until March 2008.

	Treatment number									
	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
	Plant available water depletion pre-véraison → post-véraison									
	35%→35%	75%→35%	75%→CDI[1]	75%→75%	90%→35%	90%→CDI	90%→90%	CDI	CDI→CDI	90%→PPR[2]
Month	Irrigation amounts (mm)									
April	0	0	0	0	0	0	0	0	0	0
May	0	0	0	0	0	0	0	0	0	0
June	0	0	0	0	0	0	0	0	0	0
July	0	0	0	0	0	0	0	0	0	0
August	0	0	0	0	0	0	0	0	0	0
September	12	10	10	10	9	9	9	12	12	11
October	18	0	0	0	0	0	0	11	11	0
November	39	28	28	28	21	21	21	16	16	22
December	68	23	23	23	0	0	0	2	2	25
January	97	87	70	51	64	48	25	3	33	39
February	102	102	37	26	102	37	25	2	37	65
March[3]	38	38	9	25	38	9	0	5	9	24
Total	374	288	177	163	234	124	80	51	120	186

(1) Continuous deficit irrigation where grapevines were irrigated frequently, but with low volumes of water to allow the soil to dry out gradually.
(2) Partial profile refill where the soil profile was only refilled partially during irrigations to maintain the plant available water between 40% and 60% depletion.
(3) March irrigation values is only for irrigation until grapes were harvest.

Table 3.9 The monthly irrigation amounts applied to ten different irrigation treatments on a sandy loam soil near Robertson form April 2008 until March 2009.

	Treatment number									
	T1	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**	**T9**	**T10**
	Plant available water depletion pre-véraison → post-véraison									
	35%→35%	**75%→35%**	**75%→CDI[(1)]**	**75%→75%**	**90%→35%**	**90%→CDI**	**90%→90%**	**CDI**	**CDI→CDI**	**90%→PPR[(2)]**
Month	Irrigation amounts (mm)									
April	0	0	0	0	0	0	0	0	0	0
May	0	0	0	0	0	0	0	0	0	0
June	0	0	0	0	0	0	0	0	0	0
July	0	0	0	0	0	0	0	0	0	0
August	0	0	0	0	0	0	0	0	0	0
September	14	14	13	13	14	13	12	13	13	14
October	13	0	0	0	0	0	0	10	10	0
November	35	18	18	18	0	0	0	13	13	0
December	92	38	38	38	0	0	0	19	19	0
January	89	49	23	42	53	28	23	12	38	25
February	115	115	42	17	115	42	0	10	42	47
March[(3)]	53	37	17	21	53	17	0	0	14	28
Total	411	271	151	149	235	100	35	77	149	114

(1) Continuous deficit irrigation where grapevines were irrigated frequently, but with low volumes of water to allow the soil to dry out gradually.
(2) Partial profile refill where the soil profile was only refilled partially during irrigations to maintain the plant available water between 40% and 60% depletion.
(3) March irrigation values is only for irrigation until grapes were harvest.

Table 3.10 The mean daily evapotranspiration for ten different irrigation treatments as measured from September 2006 to August 2007 in a sandy loam soil near Robertson.

	Treatment number									
	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
	Plant available water depletion pre-véraison → post-véraison									
	35%→35%	75%→35%	75%→CDI[1]	75%→75%	90%→35%	90%→CDI	90%→90%	CDI	CDI→CDI	90%→PPR[2]
Month	Evapotranspiration (mm/day)									
September 2006	0.76	0.74	0.75	0.83	0.80	0.78	0.73	0.81	0.71	0.69
October 2006	1.26	1.07	1.32	1.00	1.06	1.06	1.25	1.47	1.14	1.30
November 2006	1.74	0.86	0.76	1.01	0.25	0.26	0.27	1.31	1.00	0.28
December 2006	3.44	1.11	1.39	1.23	0.72	0.71	0.76	0.96	0.78	0.69
January 2007	3.12	1.63	1.36	1.34	1.14	0.99	1.40	1.02	1.20	0.84
February 2007	3.44	2.93	0.99	1.12	2.80	0.95	0.49	0.97	0.56	1.69
March 2007	2.47	1.91	1.03	0.75	1.38	0.97	1.11	1.00	0.74	0.71
April 2007	0.89	0.56	0.51	0.83	0.51	0.51	0.53	0.39	0.33	0.42
May 2007	0.44	0.28	0.25	0.55	0.25	0.25	0.27	0.20	0.16	0.27
June 2007	0.36	0.34	0.15	0.33	0.20	0.20	0.27	0.20	0.27	0.21
July 2007	0.33	0.34	0.35	0.35	0.34	0.34	0.32	0.33	0.33	0.35
August 2007	0.32	0.34	0.35	0.35	0.34	0.34	0.32	0.33	0.33	0.35

(1) Continuous deficit irrigation where grapevines were irrigated frequently, but with low volumes of water to allow the soil to dry out gradually.
(2) Partial profile refill where the soil profile was only refilled partially during irrigations to maintain the plant available water between 40% and 60% depletion.

Table 3.11 The mean daily evapotranspiration for ten different irrigation treatments as measured from September 2007 to August 2008 on a sandy loam soil near Robertson.

	Treatment number									
	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
	Plant available water depletion pre-véraison → post-véraison									
	35%→35%	75%→35%	75%→CDI[1]	75%→75%	90%→35%	90%→CDI	90%→90%	CDI	CDI→CDI	90%→PPR[2]
Month	Evapotranspiration (mm/day)									
September 2007	0.37	0.35	0.36	0.41	0.37	0.40	0.42	0.52	0.39	0.30
October 2007	1.41	0.53	0.44	0.45	0.51	0.48	0.45	1.39	1.28	0.49
November 2007	2.14	1.64	1.66	1.65	0.52	0.45	0.53	1.87	1.43	0.50
December 2007	2.36	1.05	1.04	0.94	0.46	0.56	0.47	0.71	0.46	1.61
January 2008	2.91	2.54	2.23	1.96	2.11	1.79	1.22	0.80	2.12	2.02
February 2008	3.17	3.04	2.12	1.18	2.86	1.84	1.31	0.52	2.14	1.76
March 2008	1.85	1.95	1.48	0.90	2.07	1.25	1.38	1.09	1.02	1.36
April 2008	0.69	0.75	0.73	0.58	0.62	0.62	0.51	0.86	0.67	0.54
May 2008	0.56	0.63	0.71	0.64	0.66	0.68	0.66	0.73	0.65	0.65
June 2008	0.10	0.12	0.14	0.11	0.12	0.10	0.10	0.11	0.12	0.12
July 2008	0.23	0.17	0.11	0.20	0.25	0.19	0.19	0.11	0.15	0.20
August 2008	0.21	0.24	0.27	0.30	0.25	0.23	0.22	0.30	0.25	0.24

(1) Continuous deficit irrigation where grapevines were irrigated frequently, but with low volumes of water to allow the soil to dry out gradually.
(2) Partial profile refill where the soil profile was only refilled partially during irrigations to maintain the plant available water between 40% and 60% depletion.

Table 3.12 The mean daily evapotranspiration for ten different irrigation treatments as measured from September 2008 to July 2009 on a sandy loam soil near Robertson.

	Treatment number									
	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
	Plant available water depletion pre-véraison → post-véraison									
	35%→35%	75%→35%	75%→CDI[(1)]	75%→75%	90%→35%	90%→CDI	90%→90%	CDI	CDI→CDI	90%→PPR[(2)]
Month	Evapotranspiration (mm/day)									
September 2008	0.49	0.23	0.29	0.35	0.39	0.32	0.35	0.38	0.38	0.26
October 2008	1.50	0.80	0.93	0.71	0.80	0.75	0.77	1.47	1.50	0.69
November 2008	2.13	0.59	0.69	0.60	0.64	0.58	0.59	1.69	1.17	0.53
December 2008	3.53	0.90	1.09	0.96	0.13	0.13	0.14	1.90	1.10	0.16
January 2009	3.20	1.76	1.58	1.10	1.27	1.11	0.66	0.84	1.48	1.10
February 2009	3.18	1.82	1.75	1.27	2.74	2.38	0.25	1.12	1.45	1.64
March 2009	3.33	1.71	1.41	1.67	2.08	1.92	0.08	0.10	1.04	1.65
April 2009	1.68	1.03	1.06	0.76	1.44	1.14	0.72	1.03	0.92	1.02
May 2009	0.30	0.29	0.28	0.30	0.29	0.30	0.31	0.32	0.31	0.30
June 2009	0.33	0.34	0.33	0.34	0.35	0.33	0.33	0.29	0.35	0.34
July 2009	0.25	0.24	0.13	0.26	0.19	0.20	0.24	0.25	0.23	0.18

(1) Continuous deficit irrigation where grapevines were irrigated frequently, but with low volumes of water to allow the soil to dry out gradually.
(2) Partial profile refill where the soil profile was only refilled partially during irrigations to maintain the plant available water between 40% and 60% depletion.

was probably the primary reason for this trend. The ET_c values of less frequently irrigated grapevines were lower compared to that of more frequent irrigated ones. The ET_c of Pinotage and Sauvignon blanc irrigated at 50% and 80% depletion level by means of micro-sprinklers was 2.5 mm/day and 2.8 mm/day, respectively (Myburgh, 2011) higher than comparable irrigation strategies in the present study under similar soil and atmospheric conditions. Similarly, ET_c values for micro-sprinkler irrigated Sultanina grapevines near Upington, where irrigation were applied at 30% PAW depletion (Myburgh, 2003) were *ca*. 3.5 mm/day higher than similar depletion level irrigations in the present study. The reason for the substantially higher ET_c of the Pinotage, Sauvignon blanc and Sultanina was because the irrigation systems wetted the total soil surface (Van Zyl, 1984; Van Zyl & Van Huyssteen, 1988). This suggested that more water evaporated from the larger wetted soil surface than the partially wetted surface due to the high evaporation rate during the first two stages of evaporation (Hillel, 1980; Myburgh, 1998). In all three seasons, ET_c decreased drastically in the post-harvest and dormant periods, *i.e.* from April to August (Tables 3.10 to 3.12). This decrease was caused by the reduction in irrigation after harvest in March, *i.e*. irrigation applied only at *ca.* 80% PAW depletion compared to the period before harvest.

During the three seasons, the mean crop coefficients (K_c) for T1 grapevines were higher compared to those of other strategies (Table 3.13). A mean peak K_c of 0.47 for T1 grapevines was obtained in February. The lowest K_c values were obtained where grapevines were irrigated at *ca.* 90% PAW (T7), as well as those irrigated by means of the CDI strategy throughout the season without receiving a refill irrigation at véraison (T8). The K_c values for grapevines irrigated at 30% to 40% PAW depletion throughout the season amounted to 0.3 during the pre-véraison period and 0.4 during ripening. Where grapevines were irrigated at high depletion levels before véraison, followed by irrigation at 30% to 40% PAW depletion during ripening, K_c was only 0.3. Irrigation at 70% to 80% PAW throughout the season, or by means of a CDI or PPR strategies, resulted in K_c values of 0.2. In the case of irrigation at *ca*. 90% PAW depletion throughout the season K_c was 0.1.

The foregoing K_c values are substantially lower than values reported for Pinotage and Sauvignon blanc under similar climatic and soil conditions, but where full surface irrigation was applied by means of micro-sprinklers (Myburgh, 2011). The K_c for high

Table 3.13 The mean monthly crop coefficients for ten different irrigation treatments as determined from September 2006 to July 2009 on a sandy loam soil near Robertson.

	Treatment number									
	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
	Plant available water depletion pre-véraison → post-véraison									
	35%→35%	75%→35%	75%→CDI[1]	75%→75%	90%→35%	90%→CDI	90%→90%	CDI	CDI→CDI	90%→PPR[2]
Month	Crop coefficients									
September	0.12	0.09	0.09	0.11	0.11	0.11	0.11	0.09	0.11	0.09
October	0.24	0.15	0.16	0.13	0.14	0.14	0.15	0.25	0.23	0.15
November	0.28	0.14	0.14	0.15	0.07	0.06	0.07	0.23	0.17	0.06
December	0.41	0.14	0.15	0.14	0.06	0.06	0.06	0.16	0.10	0.11
January	0.42	0.26	0.23	0.19	0.20	0.17	0.14	0.12	0.21	0.17
February	0.47	0.37	0.23	0.18	0.40	0.24	0.10	0.13	0.20	0.25
March	0.41	0.30	0.21	0.19	0.30	0.23	0.14	0.12	0.15	0.20
April	0.21	0.17	0.16	0.21	0.11	0.15	0.14	0.17	0.13	0.10
May	0.19	0.16	0.16	0.23	0.12	0.16	0.16	0.15	0.13	0.12
June	0.13	0.13	0.07	0.12	0.10	0.08	0.10	0.08	0.11	0.09
July	0.12	0.11	0.10	0.12	0.12	0.11	0.11	0.09	0.10	0.12
August	0.10	0.11	0.12	0.12	0.11	0.11	0.10	0.12	0.11	0.11

(1) Continuous deficit irrigation where grapevines were irrigated frequently, but with low volumes of water to allow the soil to dry out gradually.
(2) Partial profile refill where the soil profile was only refilled partially during irrigations to maintain the plant available water between 40% and 60% depletion.

frequency drip irrigated Shiraz grapevines was only 51% of that of the high frequency micro-sprinkler irrigated Pinotage and Sauvignon blanc. The K_c of less frequently drip irrigated (*ca.* 80% depletion level) Shiraz was 34% less compared to Pinotage and Sauvignon blanc grapevines irrigated at the same soil water depletion level (Myburgh, 2011). The K_c values obtained in the present study by means of irrigation at *ca.* 90% PAW depletion only amounted to 20% and 33% of the values obtained for Sultanina grapevines that were irrigated by means of wide and narrow bed flood irrigation, respectively, in the arid Lower Orange river region.

3.4. CONCLUSIONS

Grapevines irrigated by means of drip irrigation required less irrigation water than grapevines irrigated by means of micro-sprinklers at similar depletion levels in the same region. Up to four times less water was necessary to apply irrigation at an 80% depletion level with drip irrigation compared to micro-sprinkler irrigation.

Grapevines irrigated at high frequencies throughout the season had higher ET_c losses during ripening, compared to grapevines only irrigated at high PAW depletion levels before véraison and frequently during ripening. Seasonal ET_c of drip-irrigated grapevines was almost half of grapevines irrigated by means of full surface micro-sprinkler irrigation under the same soil and climatic conditions. This can be attributed to more water being readily lost through evaporation from larger wetted area. Under conditions of extremely low relative humidity, but within the same climatic region, full surface irrigations at similar soil water depletion levels will cause even higher ET_c losses compared to drip irrigation. This can be attributed to the fact that the difference between water vapour pressure at the transpiring surface and the surrounding air is the determining factor for vapour removal (Allen *et al.*, 1998) and that in low humidity arid regions, high vapour pressure deficits conditions are present.

Drip irrigation at 35%, 75% or 90% PAW depletion requirements can be obtained by applying irrigation of 0.3, 0.2 and 0.1, respectively, of the prevailing ET_o. During the ripening period, grapevines irrigated with a K_c of 0.3 before véraison will need to be irrigated with a 0.4 K_c value of ET_o to maintain a *ca*. 35% PAW depletion strategy throughout ripening. To apply a continuous deficit irrigation strategy, a K_c of 0.2

should be used, but irrigations must be applied more frequently and in smaller volumes than in the case of *ca*. 75% PAW depletion level irrigations. These K_c values could be *ca.* two to three times higher if a full surface irrigation method is used instead of a partial wetting system like drip irrigation (Van Zyl & Van Huyssteen, 1988; Myburgh, 2011).

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Chapter 4

THE RESPONSE OF SHIRAZ/110R TO DIFFERENT IRRIGATION STRATEGIES IN THE BREEDE RIVER VALLEY REGION

CHAPTER 4
GRAPEVINE RESPONSE TO DIFFERENT IRRIGATION STRATEGIES IN A SHIRAZ/110R VINEYARD IN THE BREEDE RIVER VALLEY REGION

4.1 INTRODUCTION

Evidence suggests that *Vitis vinifera* was first domesticated in the Near East during the Bronze Age around 3200 BC (McGovern, 1996). The earliest act of cultivation appears to have been the use of hermaphroditic members of *Vitis vinifera* species over male and female grapevines which were dependent on having a male pollinator nearby (Johnson, 1989). The manipulation of grapevines by means of the application of extra water through irrigation date back to *ca.* 2900 BC in Mesopotamia and Babylonia near the Euphrates River and *ca.* 1500 BC in Egypt next to the Nile River (Younger, 1966).

In modern day Europe, irrigation of wine grapevines is prohibited in most Appellation Control regions, which created the myth that irrigation and over vigorous growth is *ipso facto* inimical to grape quality (Jackson, 2000). In most grape and wine production areas, low rainfall and high evaporative demands can cause high yield losses and have a negative effect on wine quality if no supplementary irrigation is applied (Williams *et al*., 1994). As competition in world wine markets grow, the balance between optimum yield and wine quality becomes ever more important (Mehmel, 2010).

Grapevine plant water potential can be affected by many factors such as solar radiation, relative humidity, temperature, atmospheric pollutants, wind, soil environment and plant factors (Smart & Coombe, 1983). Even though Choné *et al*. (2001), Lebon *et al.* (2003), Loveys *et al.* (2004) and Pellegrino *et al.* (2004) documented that pre-dawn leaf water potential (Ψ_P) is the reference indicator of soil water potential in many species including grapevines, these measurements are not always a practical tool for irrigation scheduling at the farm level. Stem water potential measurements are regarded as a more reliable indicator of soil water induced plant stress by some researchers (Choné *et al*., 2001; Williams & Araujo, 2002; Patakas *et al*., 2005; Van Leeuwen *et al*., 2009).

An increase in vegetative growth can be expected when grapevines that are irrigated at high frequencies and/or volumes and where high soil water availability is maintained, are compared with grapevines exposed to water constraints (Van Zyl, 1981; Smart, 1982; McCarthy *et al.,* 1983; Myburgh, 1996; Myburgh, 2003; Myburgh, 2011a, Myburgh, 2011c). Grapevine water constraints due to soil water deficits have an inhibitory effect on vegetative growth and alters the grapevine phenology (Coombe & Dry, 1988), whereas there will be active shoot growth through the whole season when grapevines experience no to little water constraints (Van Zyl, 1981).

Berry size is dependent on soil water availability, particularly in the period between flowering and véraison (Van Zyl, 1984; Williams *et al*., 1994 and references therein; McCarthy, 2000; Ojeda *et al*., 2002; Girona *et al*., 2006). Matthews *et al.* (1986) suggested that smaller berries at harvest was a result of water constraints during the first two stages of berry development. Small berries have a smaller flesh to skin ratio and are therefore considered to be an important component of good wine quality for red grape cultivars (Bravdo *et al*., 1985; McCarthy, 2000; Kennedy *et al*., 2002). Management practices such as the use of less vigorous rootstocks and canopy manipulations might not be enough to ensure the production of smaller berries and the selection of an appropriate irrigation strategy plays a vital role in this manipulation process (Ellis, 2008). Bunches on grapevines subjected to soil water constraints tended to produce less compact bunches than more frequently irrigated ones (Van Zyl & Weber, 1977). Grapevine yield correlates well with irrigation volumes applied (Myburgh, 2007; Lategan & Howell, 2010; Myburgh, 2011a, Myburgh, 2011d). Chenin blanc (Van Zyl & Weber, 1977) and Colombar (Myburgh, 2007) yields did not increase indefinitely after higher irrigation volume applications, but reached a plateau after a certain amount of irrigation water was applied.

Luxurious water supply to grapevines during ripening may stimulate vegetative re-growth, these actively growing shoots compete with berries for carbohydrates synthesised by green leaves, and could result in less sugar availability for berries (Saayman, 1992). High soil water availability to grapevines after véraison can slow down sugar accumulation, thereby retarding ripening (Smart & Coombe, 1983). During this prolonged ripening period berry total titratable acidity (TTA) may start to decrease and pH increase (Smart & Coombe, 1983) as a result of grape maturity before target sugar levels are obtained (Deloire, 2010b). Such juice characteristics could have a negative effect on the wine, since there will be a high risk of micro-organism presence in the wines made from high pH juice. Furthermore, low acidity could cause wine to taste bland (Jackson & Lombard, 1993).

Grapevines subjected to water constraints tend to produce wines with better colour, more prominent cultivar characters and higher overall wine quality (Ureta & Yavar, 1982; Becker & Zimmerman, 1983; Bruwer, 2010; Ristic *et al.*, 2010; Myburgh, 2011a; Myburgh, 2011d). However, in years with extremely low rainfall, non-irrigated grapevines could be exposed to excessive water constraints to such an extent that the wines produced are of poor quality (Myburgh, 2011a). Furthermore, water constraints before véraison followed by a luxurious supply of water during ripening will result in wines with a poor colour and diluted or grassy wine characters (Ureta & Yavar, 1982; Myburgh, 2011d).

Most South African wine grape irrigation research has been carried out vineyards irrigated either by full surface flood, overhead sprinkler or micro-sprinkler irrigation (Van Zyl & Weber, 1977; Van Zyl, 1984; Myburgh, 1996; Myburgh, 1998; Myburgh, 2003; Myburgh, 2006a; Myburgh, 2011b). Consequently, there is insufficient information about the response of grapevines to drip irrigation. Hence, the aim of this study is to determine the effect of ten different drip irrigation strategies on the root system characteristics, grapevine water status, vegetative growth, yield components, juice characteristics and wine quality characteristics of Shiraz in a semi-arid region.

4.2 MATERIALS AND METHODS

Details of the Shiraz/110R vineyard on the farm Wansbek, *ca.* 23 km southwest from Robertson the Breede River Valley region, have already been presented in Chapter 3. Refer to Chapter 3 Section 3.2.2 and Table 3.1 for treatment descriptions, Tables 3.2 to 3.4 for climatic conditions and Tables 3.7 to 3.9 for seasonal irrigation volumes applied to the different irrigation strategies.

4.2.1 Root system characteristics

Root studies were carried out in each experiment plot at the conclusion of the field trial in October 2009. The profile wall method of Böhm (1979) was used to qualify root distribution within the constraints of the technique. A trench, 3 m long and 1 m deep, was excavated across the grapevine row between four experiment grapevines, with the long sides 100 mm from the grapevines. After the roots were exposed, a 100 mm x 100 mm portable wire grid was placed against the profile wall for mapping of roots. Roots were classified according to their diameter (Ø) into four classes, namely fine (Ø ≤ 2 mm), medium (2 mm < Ø ≤ 5 mm), coarse (5 mm < Ø ≤ 10 mm) and thick (Ø > 10 mm). The roots in each plot were plotted on graph paper and processed by means of Microsoft® Excel for statistical analyses. Roots were painted with white paint and photographs were taken for presentation purposes.

4.2.2 Grapevine water status

To quantify grapevine water status, water potentials were determined in mature leaves on primary shoots by means of the pressure chamber technique (Scholander *et al.*, 1965) according to the protocol described by Myburgh (2010). Pre-dawn leaf water potential (Ψ_{PD}) was measured in mature leaves between 04:00 and 04:30, *i.e.* before day break. Mid-day leaf water potential (Ψ_L) was measured in mature leaves fully exposed to the sun between 12:00 and 13:00, whereas leaves were covered in aluminium bags (Choné *et al.*, 2001; Myburgh, 2010) for at least one hour before measuring mid-day stem water potential (Ψ_S). Water potentials were determined in all treatments in one grapevine per replication plot as regularly as possible on full sunshine days. On 19 December 2007 and 20 February 2008, the diurnal variation in Ψ_L was measured at two hour intervals from 04:00 am until 02:00 am the next day. All pressure chambers used were custom built and calibrated against a precision pressure gauge. Total diurnal leaf water potential (Ψ_T) was calculated using the trapezoidal rule (Larson *et al.*, 1994) as described by Myburgh & Howell (2006).

4.2.3 Vegetative growth

Vegetative growth was quantified by measuring cane mass of the experiment grapevines in each plot during pruning in July using a hanging balance. Cane mass was calculated by converted the kilogram cane mass per experiment plot to ton per hectare. Leaves were analysed at harvest to determine whether there were any nutrient deficiencies, and to quantify the effect of the drip irrigation treatments on nutrient uptake. In the first and third seasons, 30 healthy basal leaves per plot were sampled at harvest, the petioles removed and the leaf blades placed in paper bags. The samples were dried in a fan oven at 60ºC for 24 hours. The dried leaf samples were analysed at a commercial laboratory (BEMLAB, Strand). Nitrogen content was determined using methods described by Horneck & Miller (1998) by means of a nitrogen analyser. Samples was prepared for analysis of P, K, Ca, Mg, Na, Mn, Fe, Cu, Zn and B and analysed using methods described by Isaac & Johnson (1998) by means of an ICP-OES spectrometer (PerkinElmer Optima 7300 DV, Waltham, Massachusetts, U.S.A.).

4.2.4 Yield components

Véraison was defined as the stage of the season when visual observation showed that *ca.* 95% of grape berries had changed colour. This was equivalent to stage 36 of the modified Eichhorn and Lorenz grapevine growth identification system (Coombe, 1995). All bunches in each experiment plot were picked and counted using mechanical counters. The grapes were weighed to obtain the total mass per plot. Mean yield per grapevine was calculated and converted to ton per hectare. Bunch mass was determined by dividing the total grape mass per plot by the number of bunches per plot. The number of bunches per grapevine was calculated by dividing the total number of bunches per plot by the number of experiment grapevines per plot. The irrigation water productivity (IWP) for each irrigation strategy was calculated as the fresh mass of grapes (kg) produced per cubic meter water irrigation applied to grapevines during a growing season as reported by Myburgh (2011a).

Fresh berry mass was determined in all the plots at harvest. Berry samples were obtained by picking 20 berries along the longitudinal axis from each of ten bunches per experimental plot. Berries were removed from bunches by cutting through the pedicle as close as possible to the berry using a small pair of scissors (Van Schalkwyk, 2004).

During the 2007/08 season, grapevine bunches were infected with grey rot (*Botrytis cinerea*). At harvest, each bunch was visually inspected and bunches infected by grey rot were weighed separately. Grey rot was quantified as the percentage infected bunches in relation to the total number of bunches per plot.

4.2.5 Juice characteristics

The objective was to harvest grapes when the total soluble solids (TTS) in the juice reached 24˚B. The TSS, TTA and pH of the juice were determined according to standard procedures of the Infruitec-Nietvoorbij Research Institute for Viticulture and Oenology of the Agricultural Research Council (ARC) near Stellenbosch. Total soluble solids were determined using a digital refractometer (Pocket PAL-1, Atago U.S.A. inc., Bellevue, WA, U.S.A.). Total titratable acidity and pH of the juice were measured using an automatic titrater (Metrohm 785 DMP Tritino, Metrohm AG, Herisau, Switzerland), against sodium hydroxide (NaOH) at a concentration of 0.33 M.

The mean juice cation content were analysed at a commercial laboratory (BEMLAB, Strand). Nitrogen content was determined using methods described by Clesceri *et al.* (1998) by means of a nitrogen analyser. Samples was prepared for analysis of Na, Mg, Ca, K, and P and analysed using methods described by Clesceri *et al.* (1998) by means of an ICP-OES spectrometer (PerkinElmer Optima 7300 DV, Waltham, Massachusetts, U.S.A.).

4.2.6 Wine quality characteristics

During each of the three seasons, wines were made on an experiment scale. Wines were made from grapes each of three replications of all treatments. Forty kg grapes were picked from each plot and micro-vinified at the research winery of ARC Infruitec-Nietvoorbij. After the grapes were crushed 50 mg/kg SO_2 was added. Skin contact was allowed for at least one hour before the crushed grapes were inoculated with a commercial wine yeast (VIN 13, Anchor Biotechnologies), at a concentration of 30 g/hL. A volume of 50 g/hL diammonium phosphate (DAP) was then added.

Fermentation was conducted on the skins at 25°C and the cap was punched down three times a day. The must was fermented down to between 0°B and 5°B. Following this, the skins were separated and pressed at *ca.* 0.2 MPa. The pressed wine was added to the free run-off wine and fermented at 25°C until dry. As soon as fermentation was completed, the wine was racked, the SO_2 adjusted to a total of 85 mg/L (in accordance with the analysis) and cold stabilised at 0°C for at least two weeks. After cold stabilisation the wine was filtered by using sterile mats (K900 and EK), as well as a 0.45 μm membrane and bottled into nitrogen filled bottles at room temperature. The total SO_2 was adapted during bottling to ensure that it was not less than 85 mg/L. The bottled wines were stored at 14°C until the sensorial evaluation in August of the harvest year.

Wines were subjected to sensorial evaluation by a panel of at least 12 experienced wine tasters. The primary sensorial wine characteristics were colour, flavour, taste and overall wine quality. The flavour characteristics consisted of (i) berry aroma, *i.e.* blackberry, raspberry, strawberry and black currant (ii) spicy aroma, *i.e.* black pepper, cloves, liquorice, and aniseed (iii) nutty aroma, *i.e.* almond, hazelnut and walnut and (iv) smoky aroma, *i.e.* smoke, coffee and chocolate. The taste characteristics were acidity, fullness (body) and astringency. Wine characteristics were scored by means of a 100 mm long unmarked line scale. Determining the effect of the different irrigation strategies on wine chemical composition was beyond the scope of this study.

4.2.7 Statistical analyses

Raw data was captured and sorted by using Microsoft® Excel. The data were subjected to an analysis of variance (ANOVA) by using Statgraphics®. Least significant difference (LSD) values were calculated to facilitate comparison between treatment means. Means, which differed at $p \leq 0.05$, were considered significantly different. Statgraphics® was used to fit regression models.

4.3 RESULTS AND DISCUSSION

4.3.1 Root system characteristics

The root systems consisted primarily of fine roots that were distributed mostly below the grapevine row to a depth of *ca.* 700 mm (data not shown). Due to the fact that this area do not have high rainfall during winter, the root structure present was due to the present irrigation system (Van Zyl & Van Huyssteen, 1988). Although SWC differed substantially between the different irrigation strategies as discussed in Chapter 3, it did not have any effect on the root density or distribution throughout the soil profile (data not shown). The mean root density per plot amounted to 170±55 roots/m^2. The lack of differences is illustrated by the similarity of the root distribution profiles of the grapevines subjected to the most frequent irrigated (T1) and least frequent irrigated (T7) soil conditions (Figure 4.1 & 4.2).

Previous research has indicated that more frequent irrigation induce higher grapevine root concentrations (Van Zyl, 1984; Van Zyl, 1988; Myburgh, 1996). However, it should be kept in mind that in these trials, vineyards were irrigated over the full surface by means of micro-sprinklers. Soar & Loveys (2007) reported an increase of total root mass in the 25 cm to 50 cm soil layer under the drippers for grapevines that were established under full surface irrigation systems and subsequently changed to drip irrigation. This increase in root activity under the drippers was the result of a higher fine root (Ø < 4 mm) concentration in the wetted part of the soil profile (Soar & Loveys, 2007). Van Zyl (1988) indicated that *ca*. 80% of the roots of Colombar/99R in the Breede River Valley irrigated by means of drip irrigation were distributed to a depth of reasonably well with 145 roots/m^2 reported for Chenin blanc/101-14 Mgt0.75 m under drippers. The mean root density of the current trial correlated planted in a sandy loam soil ripped to a depth of 0.8 m and irrigated by means of micro-sprinklers in the Breede River Valley (Van Huyssteen, 1988). Since the grapevines in the current study was established under drip irrigation and only irrigated to the effective root depth, a similar concentration effect was observed.

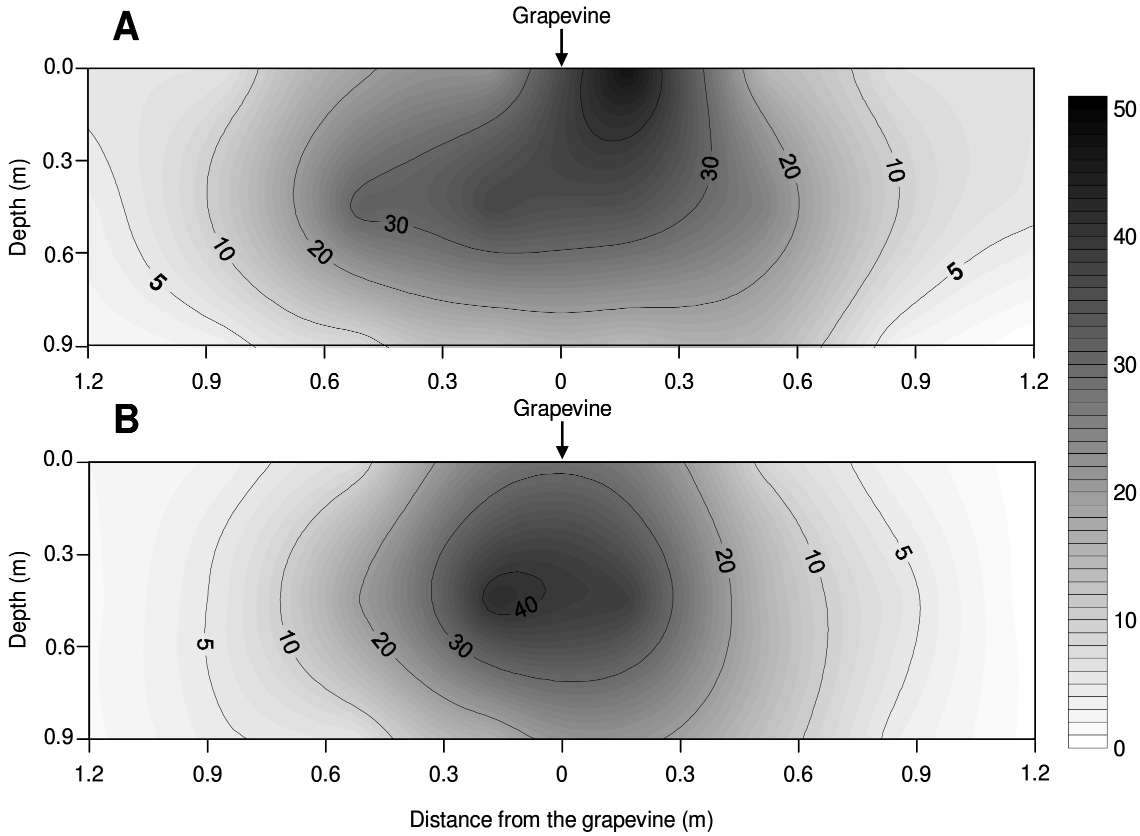

Figure 4.1 **Root distribution profile across the grapevine row of Shiraz/110R grapevines in a fine sandy loam soil that were (A) irrigated at 30% to 40% PAW depletion level (T1) and (B) irrigated at *ca.* 90% PAW depletion level (T7) near Robertson from the 2006/07 to the 2008/09 season. The scale on the right hand side of the figure indicates actual number of roots.**

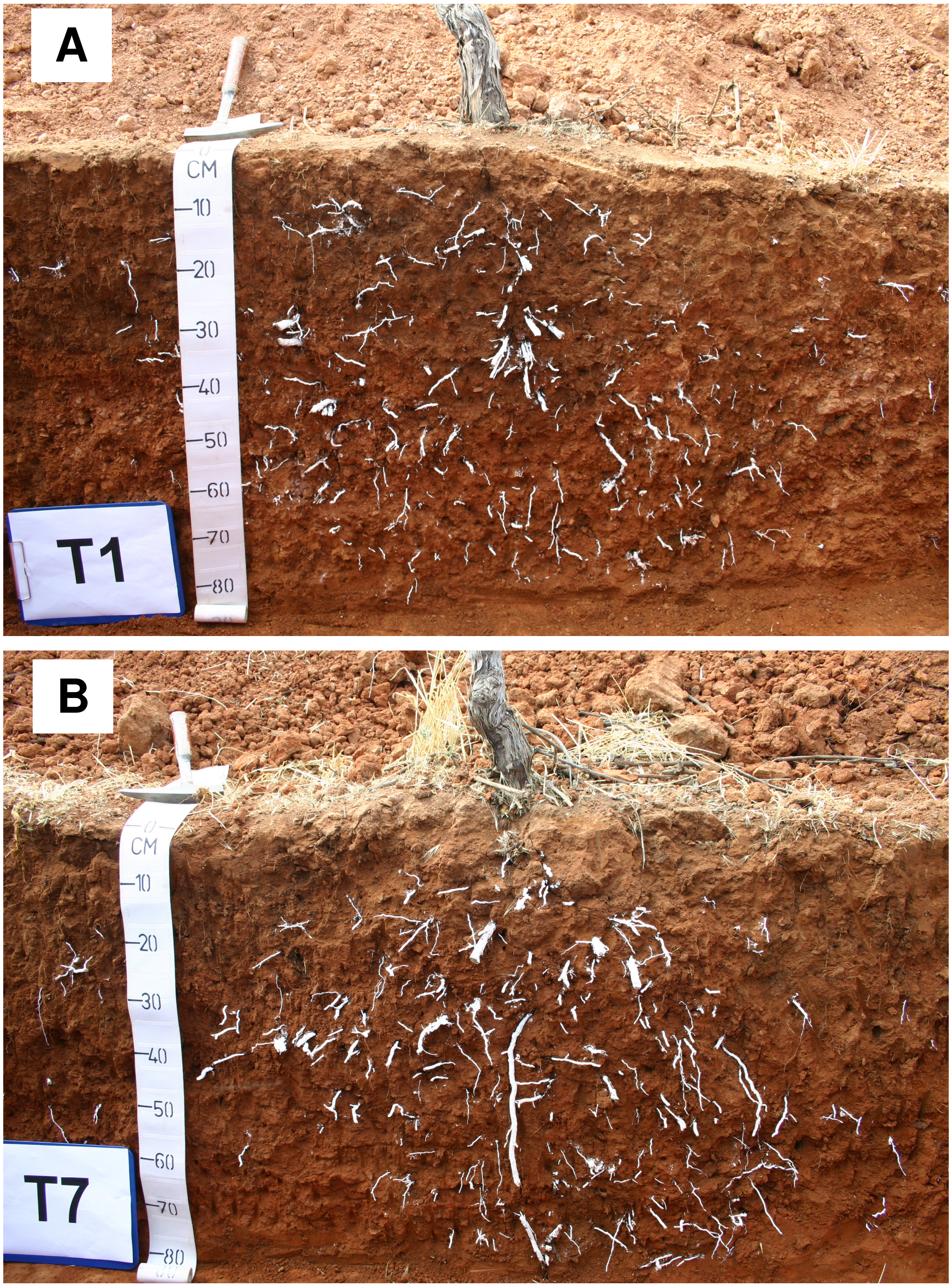

Figure 4.2 Example of the root distribution across the grapevine row of Shiraz/110R grapevines in a fine sandy loam soil that were (A) irrigated at 30% to 40% PAW depletion level (T1) and (B) irrigated at *ca.* 90% PAW depletion level (T7) near Robertson from the 2006/07 to the 2008/09 season.

4.3.2 Grapevine water status

Before the PAW levels were adjusted at véraison in mid-January, Ψ_{PD}, Ψ_L and Ψ_S in grapevines that were subjected to high PAW depletion levels, *i.e.* T2 to T10 grapevines, were significantly lower compared to the water potential in T1 ones (Tables 4.1 to 4.3). During ripening, Ψ_{PD}, Ψ_L and Ψ_S in grapevines subjected to high PAW depletion levels were lower compared to that of grapevines that were irrigated at a high frequency. This trend was consistent over the three seasons.

During the post-véraison period, the mean Ψ_{PD} and Ψ_S was *ca.* -0.3 MPa and *ca.* -0.9 MPa, respectively, in grapevines that were irrigated at 30% to 40% PAW depletion (T1, T2 & T5). At harvest, Ψ_S of *ca.* -1.5 MPa in grapevines irrigated according to the CDI strategy during ripening (T3, T6 and T9) indicated that they experienced a high level of water constraint. Mid-day Ψ_S in grapevines that were irrigated at *ca.* 80% (T4) and 90% PAW depletion (T7) was -1.6 MPa and -1.8 MPa, respectively, *i.e.* two weeks after they were irrigated. The highest level of water constraint, *i.e.* Ψ_S of *ca.* -2.1 MPa, occurred just before harvest in grapevines that were either irrigated at *ca.* 90% PAW depletion (T7), or according to the CDI strategy without the refill irrigation at véraison (T8). These trends were consistent over the three seasons.

Diurnal variations in leaf water potential over the 24 hour period for the respective days are presented in Figure 4.3. Variations in temperature, incoming solar radiation, wind speed and vapour pressure deficit on the two respective days are presented in Figures 4.4 and 4.5. The relatively low degree of differences in Ψ_{PD} and mid-day Ψ_L on 19 December 2007 (Table 4.2) was probably caused by the 25 mm rainfall that occurred on16 December 2007 (data not shown). However, mid-day Ψ_S seemed to have responded more readily to variations in the soil water status (Table 4.4). The total diurnal leaf water potential in grapevines irrigated according to the T7, T8, T9 and T10 strategies was significantly higher than in T1 ones (Table 4.4).

On 20 February 2008, PAW depletion levels reflected to a higher extent in Ψ_L compared to those measured on 19 December 2007 (Figure 4.3). Although Ψ_{PD} in T1, T2 and T5 grapevines were comparable, mid-day water constraints (Ψ_L)in the T5 ones was significantly lower compared to T1, but not lower than the constraints in the T2 grapevines (Table 4.2). This can be attributed to the fact that T1 grapevines

Table 4.1 Effect of ten irrigation strategies on pre-dawn, mid-day leaf and stem water potential in Shiraz/110R grapevines in a fine sandy loam soil near Robertson as measured during the 2006/07 season.

	Treatment number									
	T1	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**	**T9**	**T10**
	Plant available water depletion pre-véraison → post-véraison									
	35%→35%	**75%→35%**	**75%→CDI[1]**	**75%→75%**	**90%→35%**	**90%→CDI**	**90%→90%**	**CDI**	**CDI→CDI**	**90%→PPR[2]**
Date	**Pre-dawn leaf water potential (MPa)**									
20/02/2007[3]	-0.59 a[4]	-0.69 abc	-0.91 cd	-0.62 ab	-0.54 a	-0.94 de	-0.98 de	-1.18 e	-0.93 cd	-0.84 bcd
	Mid-day leaf water potential (MPa)									
14/12/2006	-1.85 a	-1.90 ab	-1.94 abc	-1.98 abc	-2.08 c	-2.01 bc	-1.98 abc	-2.03 bc	-2.01 bc	-1.96 abc
20/02/2007	-1.33 a	-1.45 ab	-1.88 cd	-1.49 ab	-1.33 a	-1.68 bc	-2.15 d	-1.84 cd	-1.86 cd	-1.61 abc
	Mid-day stem water potential (MPa)									
14/12/2006	-1.03 a	-1.70 bc	-1.58 b	-1.68 bc	-1.57 b	-1.90 c	-1.55 b	-1.68 bc	-1.68 bc	-1.60 b
20/02/2007	-0.87 a	-0.85 a	-1.59 cd	-0.89 a	-0.72 a	-1.41 bc	-1.75 d	-1.50 c	-1.54 c	-1.23 b

[1] Continuous deficit irrigation where grapevines were irrigated frequently, but with low volumes of water to allow the soil to dry out gradually.
[2] Partial profile refill where the soil profile was only refilled partially during irrigations to maintain the plant available water between 40% and 60% depletion.
[3] Véraison, *i.e.* > 95% of grape berries changed colour, was observed on 15 January 2007.
[4] Values designated by the same letter within each row do not differ significantly ($p \leq 0.05$).

Table 4.2 Effect of ten irrigation strategies on pre-dawn, mid-day leaf and stem water potential in Shiraz/110R grapevines in a fine sandy loam soil near Robertson as measured during the 2007/08 season.

	Treatment number									
	T1	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**	**T9**	**T10**
	Plant available water depletion pre-véraison → post-véraison									
	35%→35%	**75%→35%**	**75%→CDI[1]**	**75%→75%**	**90%→35%**	**90%→CDI**	**90%→90%**	**CDI**	**CDI→CDI**	**90%→PPR[2]**
Date	**Pre-dawn leaf water potential (MPa)**									
19/12/2007[3]	-0.33 a[4]	-0.45 ab	-0.43 ab	-0.38 a	-0.52 ab	-0.52 ab	-0.51 ab	-0.61 b	-0.62 b	-0.48 ab
20/02/2008	-0.28 a	-0.29 a	-0.42 ab	-0.83 c	-0.28 a	-0.53 b	-0.55 b	-0.95 c	-0.58 b	-0.30 a
	Mid-day leaf water potential (MPa)									
20/11/2007	-1.52 a	-1.50 a	-1.53 a	-1.58 abc	-1.65 abc	-1.74 c	-1.72 bc	-1.58 ab	-1.59 abc	-1.62 abc
19/12/2007	-1.20 a	-1.27 ab	-1.28 ab	-1.28 ab	-1.40 ab	-1.46 ab	-1.52 b	-1.49 ab	-1.54 b	-1.47 ab
17/01/2008	-1.57 a	-1.90 b	-2.02 b	-1.90 b	-2.03 b	-2.03 b	-2.09 b	-2.10 b	-2.00 b	-1.97 b
20/02/2008	-1.56 b	-1.47 ab	-1.80 c	-1.87 cd	-1.37 a	-1.78 c	-1.87 cd	-2.02 d	-1.78 c	-1.58 b
05/03/2008	-1.67 cd	-1.43 ab	-1.88 e	-1.94 ef	-1.40 a	-1.68 bc	-1.83 de	-2.09 f	-1.87 e	-1.60 bc
	Mid-day stem water potential (MPa)									
20/11/2007	-1.21 a	-1.21 a	-1.22 a	-1.26 ab	-1.38 cd	-1.48 d	-1.48 d	-1.35 bc	-1.31 abc	-1.42 cd
19/12/2007	-0.73 a	-0.84 ab	-0.84 ab	-0.84 ab	-1.05 bc	-0.97 abc	-1.14 c	-1.20 c	-1.15 c	-1.00 bc
17/01/2008	-1.05 a	-1.62 b	-1.68 bc	-1.60 b	-1.66 b	-1.94 c	-1.78 bc	-1.88 bc	-1.88 bc	-1.63 b
20/02/2008	-0.82 a	-0.83 a	-1.33 b	-1.68 c	-0.80 a	-1.62 c	-1.50 bc	-1.92 d	-1.59 c	-0.98 a
05/03/2008	-1.07 bc	-0.98 ab	-1.61 fg	-1.69 gh	-0.87 a	-1.47 e	-1.29 d	-1.82 h	-1.52 ef	-1.18 cd

[1] Continuous deficit irrigation where grapevines were irrigated frequently, but with low volumes of water to allow the soil to dry out gradually.
[2] Partial profile refill where the soil profile was only refilled partially during irrigations to maintain the plant available water between 40% and 60% depletion.
[3] Véraison, *i.e.* > 95% of grape berries changed colour, was observed on 18 January 2008.
[4] Values designated by the same letter within each row do not differ significantly ($p \leq 0.05$).

Table 4.3 Effect of ten irrigation strategies on pre-dawn, mid-day leaf and stem water potential in Shiraz/110R grapevines in a fine sandy loam soil near Robertson as measured during the 2008/09 season.

	Treatment number									
	T1	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**	**T9**	**T10**
	Plant available water depletion pre-véraison → post-véraison									
	35%→35%	**75%→35%**	**75%→CDI[1]**	**75%→75%**	**90%→35%**	**90%→CDI**	**90%→90%**	**CDI**	**CDI→CDI**	**90%→PPR[2]**
Date	**Pre-dawn leaf water potential (MPa)**									
14/01/2009[3]	-0.28 a[4]	-0.90 bcde	-0.81 bc	-0.82 bcd	-0.84 bcde	-0.96 e	-0.92 cde	-0.79 b	-0.94 e	-0.93 de
23/01/2009	-0.26 a	-0.26 a	-0.49 bcd	-0.54 bcd	-0.36 ab	-0.54 bcd	-0.55 cd	-0.64 d	-0.43 abc	-0.60 cd
30/01/2009	-0.38 ab	-0.38 ab	-0.59 bc	-0.49 ab	-0.34 a	-0.59 bc	-0.72 c	-1.06 d	-0.52 abc	-0.49 ab
05/02/2009	-0.28 a	-0.35 a	-0.62 b	-0.64 b	-0.27 a	-0.58 b	-0.88 c	-1.12 d	-0.68 b	-0.62 b
11/02/2009	-0.32 a	-0.33 a	-0.50 b	-0.69 c	-0.33 a	-0.44 ab	-0.81 c	-0.49 b	-0.47 b	-0.53 b
26/02/2009	-0.14 a	-0.18 a	-0.30 b	-0.57 c	-0.16 a	-0.35 b	-0.73 d	-0.84 e	-0.36 b	-0.28 b
	Mid-day leaf water potential (MPa)									
05/02/2009	-1.68 a	-1.63 a	-2.05 bc	-2.05 bc	-1.68 a	-2.09 bcd	-2.17 cd	-2.22 d	-2.08 bcd	-1.95 b
11/02/2009	-0.99 ab	-0.90 a	-1.31 bcd	-1.08 abc	-0.99 ab	-1.46 cde	-1.72 e	-1.73 e	-1.54 de	-1.11 abc
26/02/2009	-1.22 a	-1.25 a	-1.68 b	-1.96 c	-1.25 a	-1.73 b	-2.02 c	-2.22 d	-1.76 b	-1.66 b
	Mid-day stem water potential (MPa)									
10/12/2008	-0.91 a	-1.27 bcd	-1.17 b	-1.28 cd	-1.26 bcd	-1.29 cd	-1.29 cd	-1.27 bcd	-1.20 bc	-1.33 d
14/01/2009	-0.63 a	-1.44 cd	-1.52 cd	-1.57 cd	-1.49 cd	-1.64 d	-1.52 cd	-1.11 b	-1.13 b	-1.41 c
23/01/2009	-0.83 a	-0.89 a	-1.13 bc	-1.50 d	-0.98 ab	-1.28 c	-1.27 c	-1.61 d	-1.28 c	-1.53 d
30/01/2009	-0.95 a	-0.93 a	-1.08 a	-1.08 a	-1.01 a	-1.23 a	-1.68 b	-1.99 b	-1.29 a	-1.27 a
05/02/2009	-1.17 a	-1.09 a	-1.71 bc	-1.69 bc	-1.05 a	-1.87 c	-1.87 c	-2.21 d	-1.78 bc	-1.54 b
11/02/2009	-0.78 a	[5]	[5]	-0.74 a	-0.71 a	[5]	[5]	-1.41 b	-1.46 b	[5]
26/02/2009	-0.76 a	-0.70 a	-1.38 bc	-1.81 d	-0.69 a	-1.48 c	-1.84 de	-2.08 e	-1.46 c	-1.18 b

[1] Continuous deficit irrigation where grapevines were irrigated frequently, but with low volumes of water to allow the soil to dry out gradually.
[2] Partial profile refill where the soil profile was only refilled partially during irrigations to maintain the plant available water between 40% and 60% depletion.
[3] Véraison, *i.e.* > 95% of grape berries changed colour, was observed on 17January 2009.
[4] Values designated by the same letter within each row do not differ significantly ($p \leq 0.05$).
[5] Mid-day stem water potentials of these treatments were not measured.

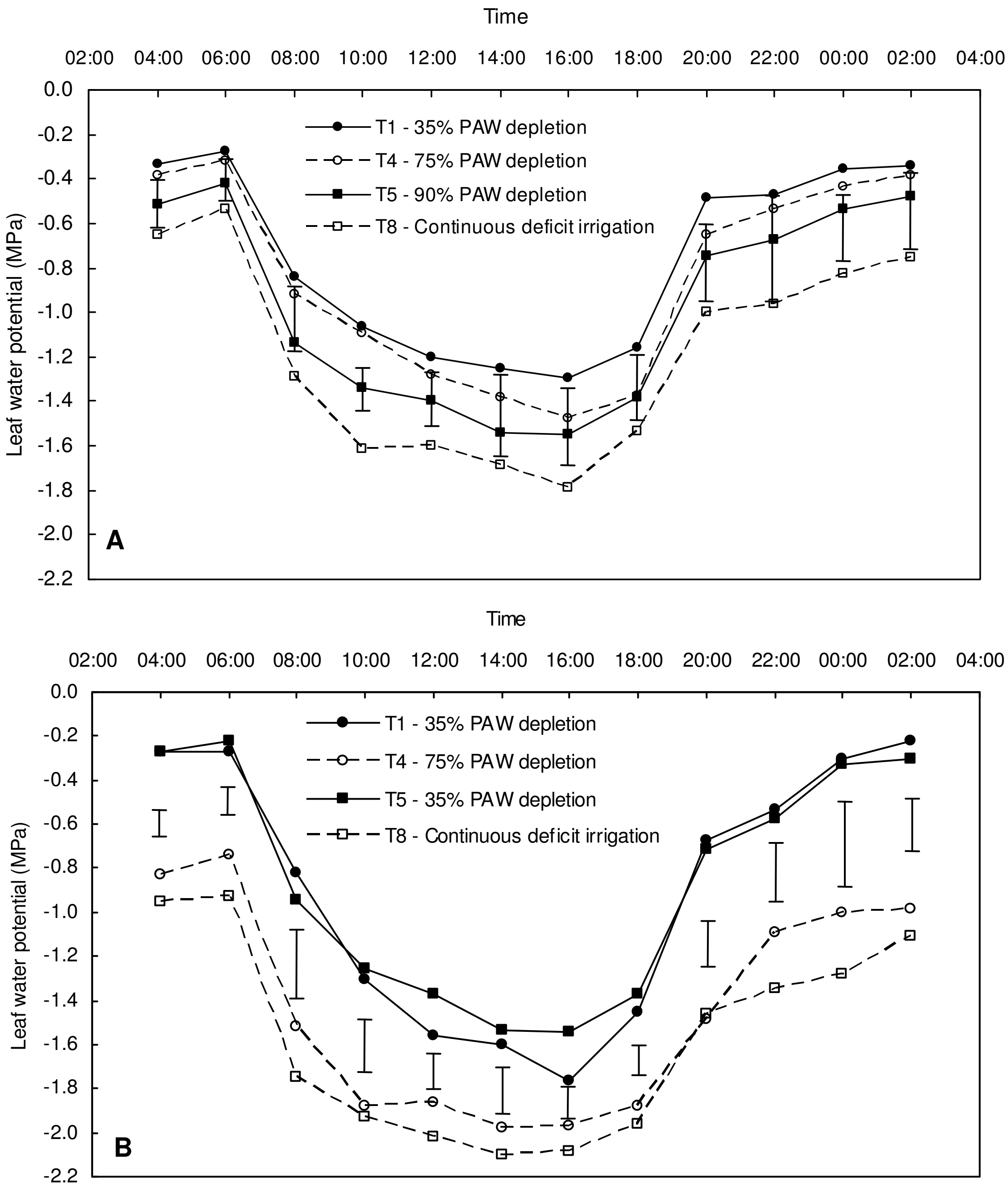

Figure 4.3 Effect of plant available water (PAW) depletion and continuous deficit irrigation on diurnal leaf water potential in Shiraz/110R grapevines in a fine sandy loam soil measured on (A) 19 December 2007 and (B) 20 February 2008 near Robertson. Vertical bars indicate least significant difference (p≤0.005).

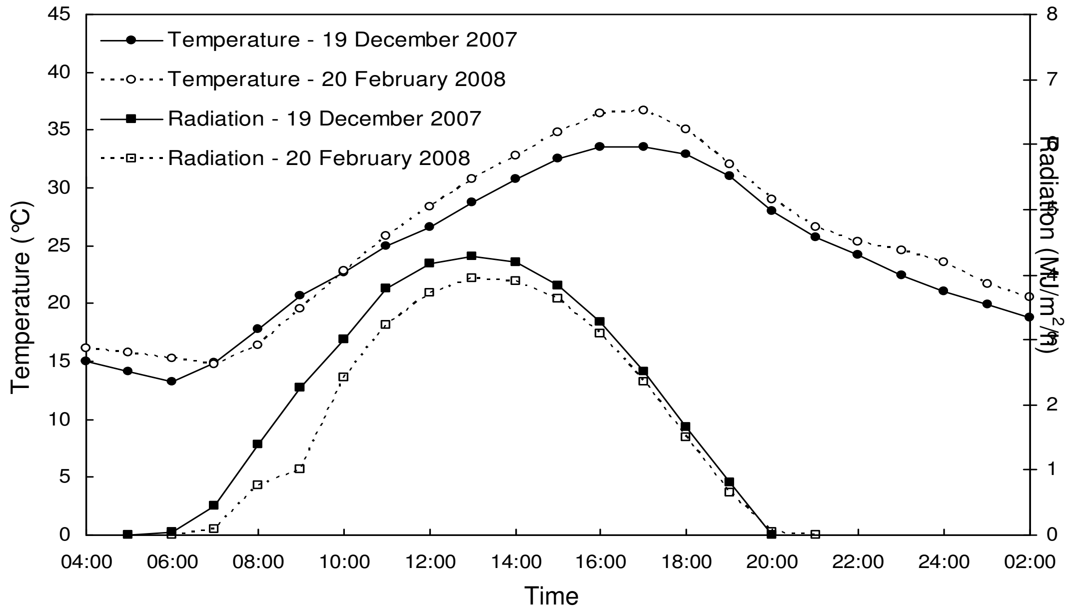

Figure 4.4 Diurnal variation in air temperature and incoming solar radiation (R_n) on 19 December 2007 and 20 February 2008, respectively, near Robertson.

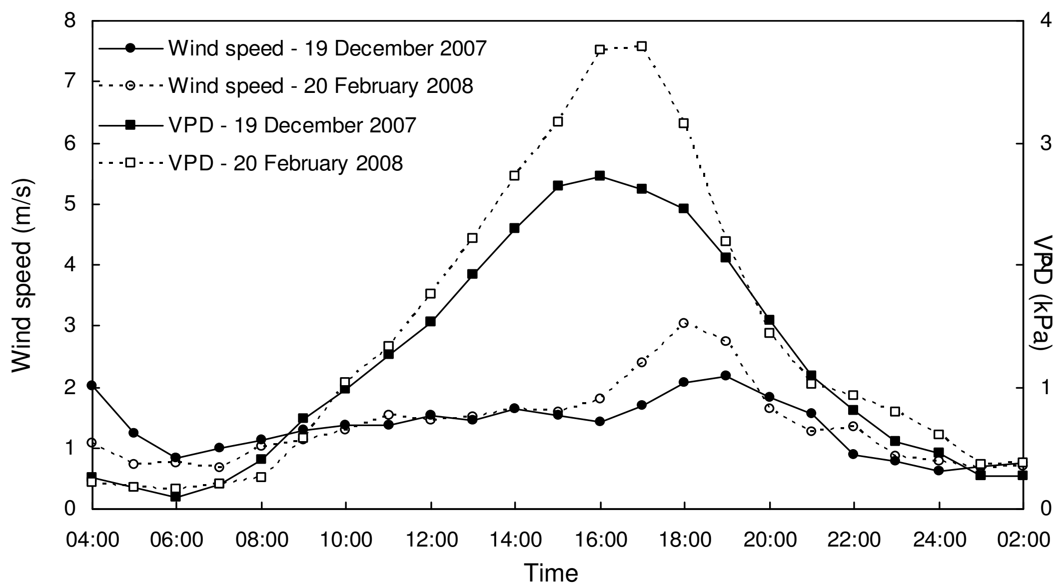

Figure 4.5 Diurnal variation in wind speed and vapour pressure deficit (VPD) on 19 December 2007 and 20 February 2008, respectively, near Robertson.

Table 4.4 Effect of ten irrigation strategies on the cumulative diurnal leaf water potential (Ψ_T) in Shiraz/110R grapevines in a fine sandy loam soil near Robertson as measured pre-véraison (19/12/2007) and before harvest (20/02/2008) during the 2007/08 season.

	Treatment number									
	T1	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**	**T9**	**T10**
	Plant available water depletion pre-véraison → post-véraison									
	35%→35%	**75%→35%**	**75%→CDI[(1)]**	**75%→75%**	**90%→35%**	**90%→CDI**	**90%→90%**	**CDI**	**CDI→CDI**	**90%→PPR[(2)]**
Time	**Ψ_T on 19 December 2007 (MPa^2)**									
04:00-08:00	1.7 d[(3)]	1.8 cd	1.8 d	1.9 bcd	2.5 abc	2.3 abcd	2.6 abc	2.8 a	2.6 ab	2.3 abcd
10:00-18:00	9.7 d	10.3 cd	10.5 cd	10.8 bcd	11.7 abc	11.7 abc	11.9 abc	12.6 ab	12.7 a	10.1 abc
20:00-02:00	2.5 c	2.9 bc	3.1 abc	3.0 abc	3.6 abc	3.8 abc	4.4 ab	4.7 a	4.2 abc	4.1 abc
Total	*13.9 d*	*15.0 cd*	*15.4 bcd*	*15.7 bcd*	*17.8 abcd*	*17.8 abcd*	*18.9 abc*	*20.3 a*	*19.7 ab*	*18.5 abc*
	Ψ_T on 20 February 2008 (MPa^2)									
04:00-08:00	1.7 d	1.7 d	2.5 c	3.8 b	1.7 d	2.6 c	2.9 c	4.6 a	2.7 c	1.7 d
10:00-18:00	12.6 de	11.8 ef	14.5 c	15.4 b	11.5 f	14.5 c	14.9 bc	16.3 a	14.6 bc	12.8 d
20:00-02:00	2.6 d	2.6 d	4.8 c	6.7 b	2.8 d	4.9 c	4.8 c	7.8 a	5.1 c	3.0 d
Total	*16.9 de*	*16.1 e*	*21.8 c*	*25.9 b*	*16.0 e*	*22.0 c*	*22.6 c*	*28.7 a*	*22.4 c*	*17.5 d*

(1) Continuous deficit irrigation where grapevines were irrigated frequently, but with low volumes of water to allow the soil to dry out gradually.
(2) Partial profile refill where the soil profile was only refilled partially during irrigations to maintain the plant available water between 40% and 60% depletion.
(3) Values designated by the same letter within each row do not differ significantly ($p \leq 0.05$).

visually had a higher total leaf area and more dense canopies compared to the T2 and T5 ones. It was previously shown that grapevines with a higher leaf area could result in lower Ψ_L than grapevines bearing a lower leaf area (Santesteban & Royo, 2006). The T10 grapevines showed the same level of mid-day water constraints as in T1 ones, although the SWC was maintained between 40% and 60% PAW depletion. The low level of water constraints in T10 grapevines was probably caused by the relatively wet top soil (data not shown). The water status in grapevines irrigated according to the other strategies differed significantly from the ones mentioned above (Table 4.2). The Ψ_T in T8 and T4 grapevines was higher than in those that were irrigated at 30% to 40% PAW depletion, *i.e.* T1, T2 and T5 (Table 4.4). Differences in the Ψ_T in T4, T7 and T8 grapevines can be attributed to the different levels of PAW depletion of each irrigation strategy on the particular date. On 20 February 2008, the SWC of the T4 and T8 strategies had been depleted to 85% and 90%, respectively. It should be noted that the SWC of the T4 strategy was beyond the refill depletion level. On the other hand, the SWC of the T7 strategy had only been depleted to 79%, and had not yet reached the target refill level of 90% PAW depletion (Table 4.4). The Ψ_T in grapevines of strategies that were being irrigated at the same depletion levels, *i.e.* T1, T2 & T5 were comparable (Table 4.4). Likewise, Ψ_T in T3, T6 & T9 grapevines responded similarly to their specific soil water depletion level. Although mid-day Ψ_L values were substantially lower than the mid-day Ψ_S values, there was a good correlation between Ψ_L and Ψ_S values (Figure 4.6). This was in agreement with earlier findings (Williams & Araujo, 2002). The Ψ_{PD}, Ψ_L, Ψ_S and Ψ_T also correlated non-linearly with the PAW in the soil profile (Figure 4.7, 4.8 & 4.9). However, perusal of the data showed that the correlation for Ψ_L was only significant for grapevines that were not irrigated a day prior to water potential measurements. This was probably because Ψ_L exhibited a delayed response to the sudden increase in soil water content. It was previously shown that Ψ_{PD} and Ψ_S responded more rapidly to SWC than Ψ_L after grapevines were irrigated (Choné *et al.*, 2001).

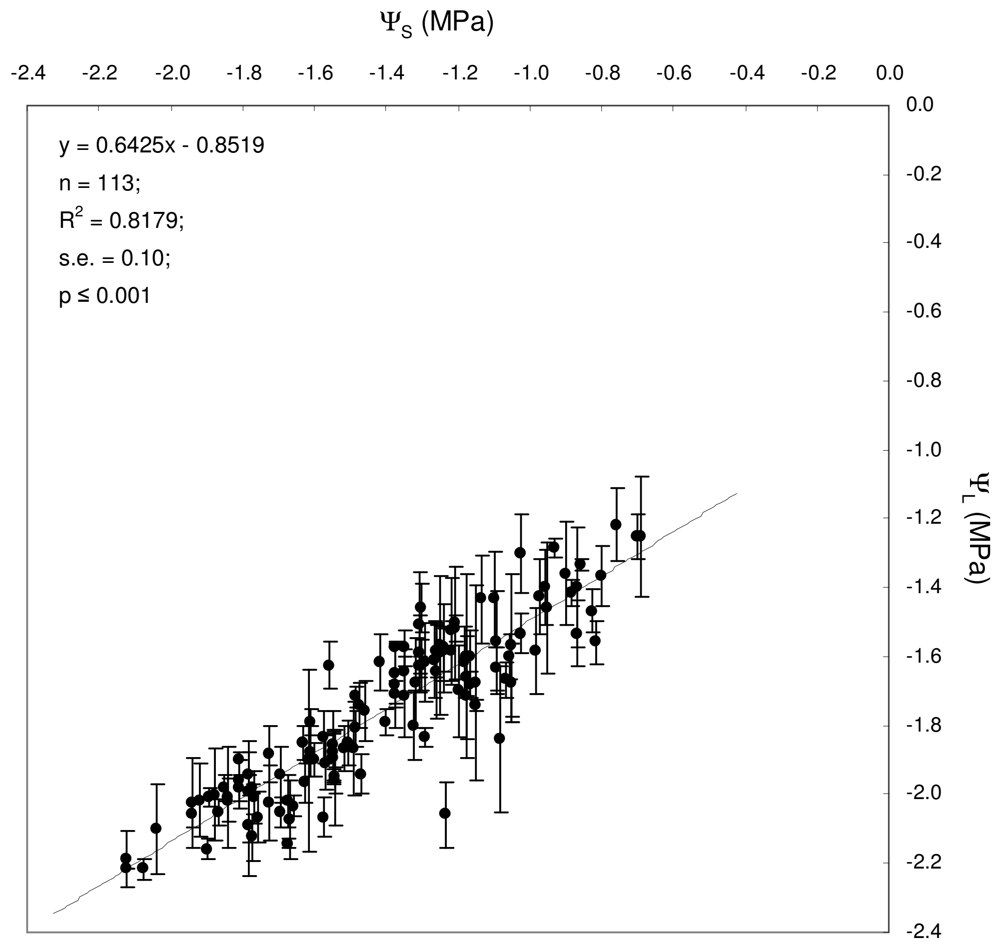

Figure 4.6 Relationship between mid-day leaf (Ψ_L) and stem (Ψ_S) water potentials of Shiraz/110R grapevines in a fine sandy loam soil as measured in the 2007/08 and 2008/09 seasons near Robertson. Vertical bars indicate standard deviation (n = 3).

Even though some grapevines were subjected to SWC levels close to field water capacity (FC), no grapevines fell in the “no stress” class as proposed by Ojéda *et al.* (2002) or Van Leeuwen *et al.* (2009). The fact that Shiraz grapevines show a more anisohydric behaviour than other cultivars (Schultz, 2003) implies that water potentials in Shiraz will be lower than in other cultivars exposed to similar soil water availability. The reason for this behaviour is that the stomata in Shiraz leaves will stay open longer until SWC is depleted (Schultz, 2003). Under similar soil and atmospheric conditions, Ψ_{PD} in Pinotage and Sauvignon blanc irrigated at 75% PAW depletion (Myburgh, 2011b) were 0.23 MPa and 0.32 MPa, respectively, higher than in Shiraz irrigated at a comparable depletion level. The Ψ_{PD} in Pinotage and Sauvignon blanc irrigated at 50% soil water depletion level (Myburgh, 2011b) were similar to that in Shiraz grapevines irrigated at 40% PAW depletion in this study.

The Ψ_L, Ψ_S and Ψ_T correlated reasonably well with Ψ_{PD} (Figure 4.10 & 4.11). Using the water stress classes by Ojéda *et al.* (2002), in conjunction with norms proposed by Van Leeuwen *et al.* (2009), water constraint classes were established for Shiraz under the conditions of this study (Figure 4.10 & 4.11). According to the relationship between Ψ_P and SWC the Ψ_{PD} did not decrease substantially up to *ca.* 40% PAW depletion (Figure 4.7). In this SWC range Ψ_{PD} varied between -0.2 MPa and -0.4 MPa. Therefore, for Shiraz grapevines in the Breede River region “no stress” in terms of Ψ_{PD} should be considered as -0.4 MPa and higher. Hence, 0.2 MPa increments below -0.4 MPa were used to create water constraint thresholds according to Ψ_{PD} for Shiraz under the given conditions. The equations presented in Figures 4.10 and 4.11 where used to calculate water constraint thresholds for Ψ_L, Ψ_S and Ψ_T from the Ψ_{PD} values (Table 4.5).

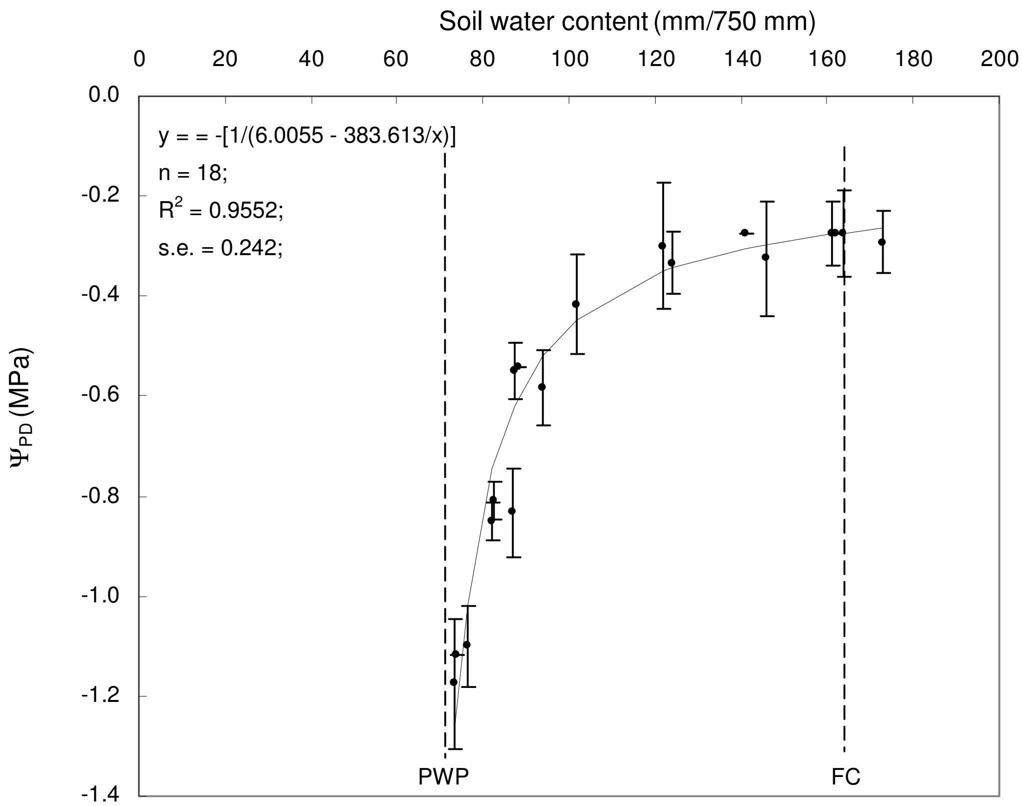

Figure 4.7 Relationship between predawn leaf water potential (Ψ_{PD}) in Shiraz/110R grapevines and the soil water content of a fine sandy loam soil as measured in the 2007/08 and 2008/09 seasons near Robertson. Dashed vertical lines indicate permanent wilting point (PWP) and field capacity (FC). Vertical bars indicate standard deviation (n = 3).

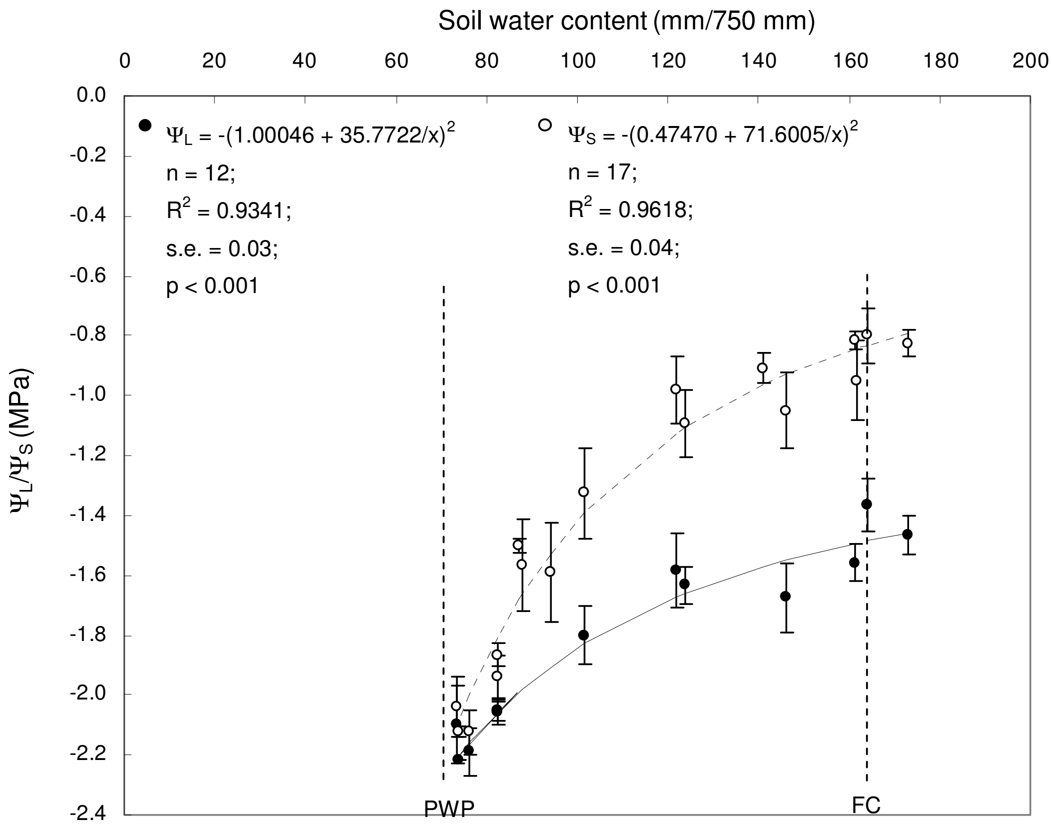

Figure 4.8 Relationship between mid-day leaf (Ψ_L) and stem (Ψ_S) water potentials in Shiraz/110R grapevines and the soil water content of a fine sandy loam soil as measured in the 2007/08 and 2008/09 seasons near Robertson. Dashed vertical lines indicate permanent wilting point (PWP) and field capacity (FC). Vertical bars indicate standard deviation (n = 3).

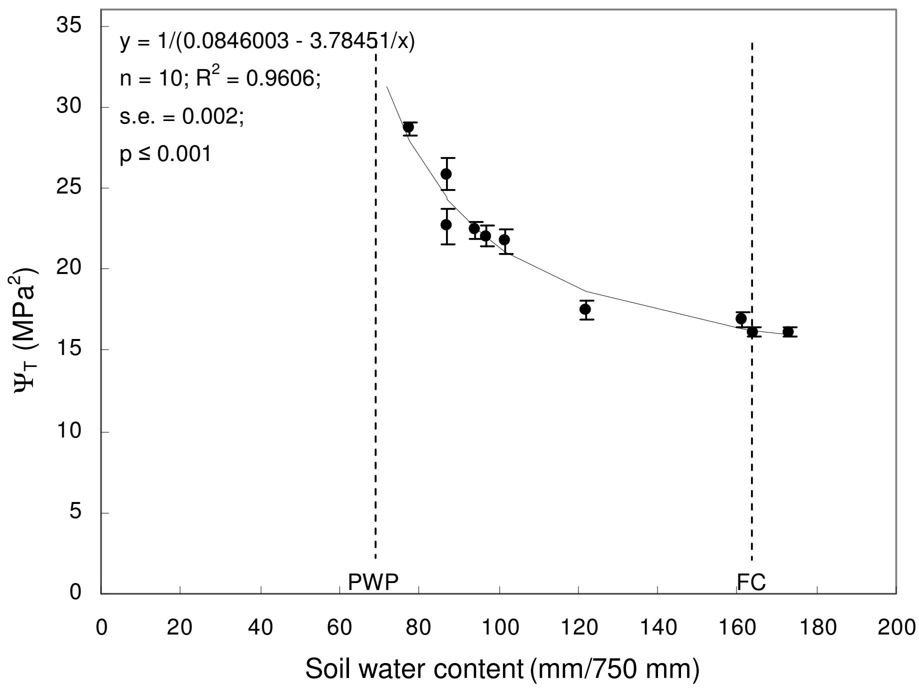

Figure 4.9 Relationship between total diurnal leaf water potential (Ψ_T) in Shiraz/110R grapevines and the soil water content of a fine sandy loam soil as measured in the 2007/08 season near Robertson. Dashed vertical lines indicate permanent wilting point (PWP) and field capacity (FC). Vertical bars indicate standard deviation (n = 3)

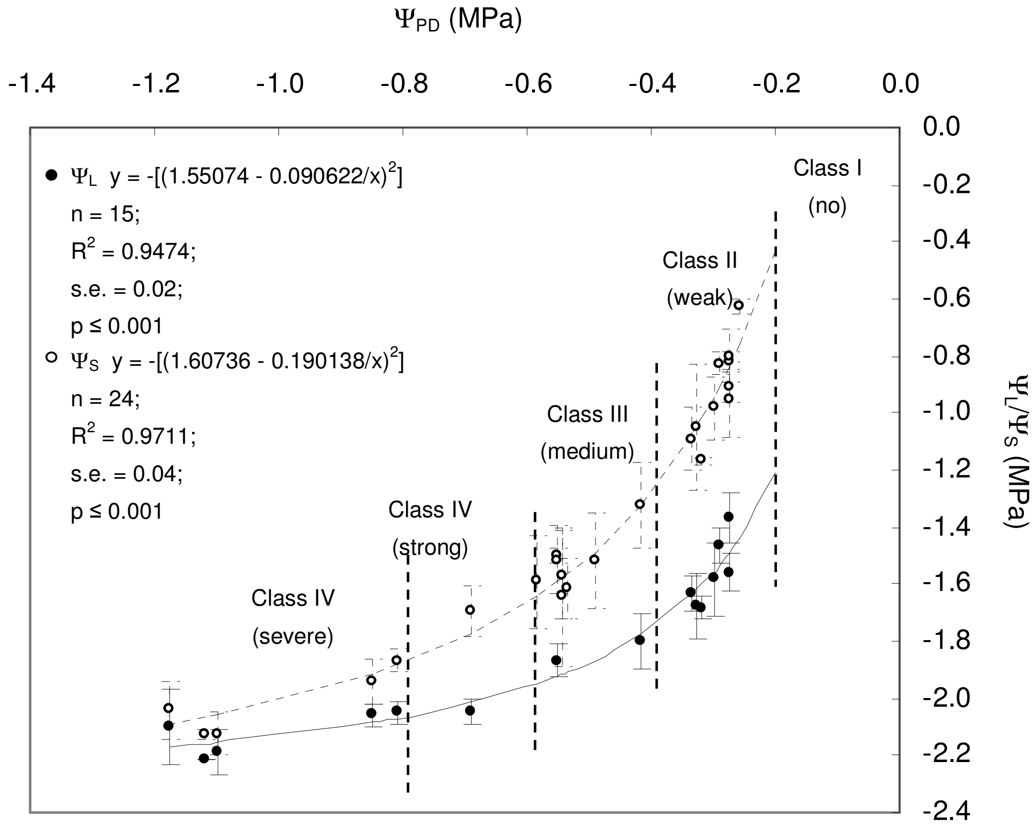

Figure 4.10 Relationship between mid-day leaf (Ψ_L) and stem (Ψ_S) water potentials and predawn leaf water potential (Ψ_{PD}) in Shiraz/110R grapevines and the soil water content of a fine sandy loam soil as measured in the 2007/08 and 2008/09 seasons near Robertson. Dashed vertical lines indicate thresholds for Ψ_{PD} water stress as proposed by Ojéda *et al.* (2002). Vertical bars indicate standard deviation (n = 3).

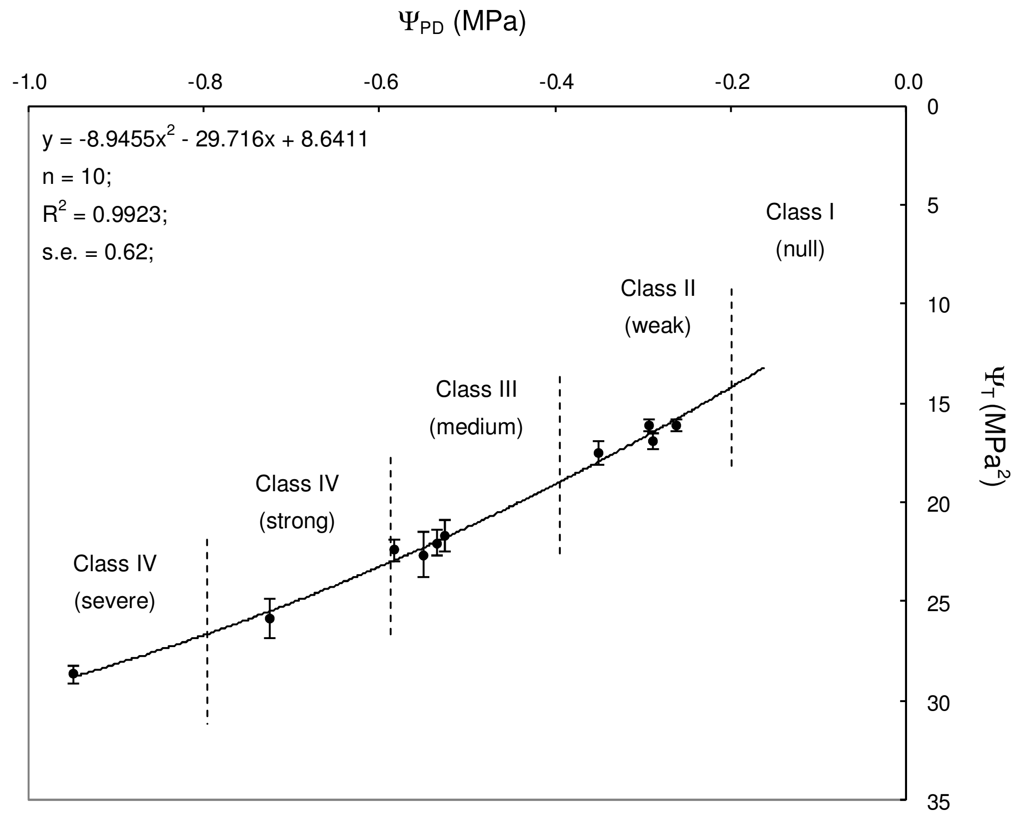

Figure 4.11 Relationship between total diurnal leaf water potential (Ψ_T) and predawn leaf water potential (Ψ_{PD}) in Shiraz/110R grapevines and the soil water content of a fine sandy loam soil as measured in the 2007/08 season near Robertson. Dashed vertical lines indicate thresholds for Ψ_{PD} water stress as proposed by Ojéda *et al.* (2002). Vertical bars indicate standard deviation (n = 3).

Table 4.5 Adapted water stress thresholds for leaf (Ψ_L), stem (Ψ_S) and total diurnal (Ψ_T) water potential in Shiraz/110R near Robertson as estimated from the pre-dawn leaf water potential (Ψ_{PD}) water stress classifications as proposed by Ojeda *et al.* (2002) and Van Leeuwen *et al.* (2009).

Class	Water stress	Water potential thresholds			
		(MPa)	(MPa)	(MPa)	(MPa^2)
I	None	$\Psi_{PD} \geq -0.4$	$\Psi_L \geq -1.8$	$\Psi_S \geq -1.3$	$\Psi_T \leq 14.2$
II	Weak	$-0.4 > \Psi_{PD} \geq -0.6$	$-1.8 > \Psi_L \geq -2.0$	$-1.3 > \Psi_S \geq -1.7$	$14.2 < \Psi_T \leq 19.1$
III	Medium	$-0.6 > \Psi_{PD} \geq -0.8$	$-2.0 > \Psi_L \geq -2.1$	$-1.7 > \Psi_S \geq -1.9$	$19.1 < \Psi_T \leq 23.3$
IV	Strong	$-0.8 > \Psi_{PD} \geq -1.0$	$-2.1 > \Psi_L \geq -2.2$	$-1.9 > \Psi_S \geq -2.0$	$23.3 < \Psi_T \leq 26.7$
V	Severe	$\Psi_{PD} < -1.0$	$\Psi_L < -2.2$	$\Psi_S < -2.0$	$\Psi_T > 26.7$

4.3.3 Vegetative growth

During the three seasons, grapevines that were irrigated at 30% to 40% PAW depletion (T1) produced the highest cane mass compared to most of the other deficit irrigation strategies (Table 4.6). The status of grapevine canopies before harvest in the 2008/09 season is shown in Figures 4.12 to 4.14. Visual observation revealed that actively growing shoot tips occurred throughout the season where grapevines were irrigated at 30% to 40% PAW depletion (T1), even after shoots were topped. The continued growth resulted in visibly more dense canopies. Shoot growth of grapevines that were subjected to high PAW depletion levels or the CDI strategy before véraison had stopped by mid-December. This occurred in all three seasons. Re-growth of shoot tips was also observed when soil water content was increased by more frequent irrigation after véraison (T2 & T5) (Figure 4.15). The cane mass of grapevines subjected to high water constraints, *i.e.* irrigation at *ca.* 75% and *ca*. 90% PAW depletion, before and after véraison, compared well with cane mass of Pinotage grapevines irrigated at similar depletion levels and under similar conditions (Myburgh, 2011b). Previous studies also showed that an increase in vegetative growth occurred when grapevines were exposed to higher irrigation volumes or frequencies (Smart, 1982; Van Zyl, 1981; McCarthy *et al.,* 1983; Myburgh, 1996; Myburgh, 2003; Myburgh, 2011a, Myburgh, 2011b).

During ripening, canopies of T8 grapevines had a pale light green colour and yellow leaves were visible in the bunch zones. Within a week after a leaf had turned yellow, senescence normally occurred. This was also observed three weeks before harvest in the case of T6 and T7 grapevines. The leaf shed visibly increased bunch exposure to direct sunlight during the berry ripening phase compared to the other treatments. Similar trends were observed during all three seasons.

Table 4.6 Effect of ten irrigation strategies on the vegetative growth of Shiraz/110R in a fine sandy loam soil near Robertson during the 2006/07, 2007/08 and 2008/09 seasons.

	Treatment number									
	T1	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**	**T9**	**T10**
	Plant available water depletion pre-véraison → post-véraison									
	35%→35%	**75%→35%**	**75%→CDI[1]**	**75%→75%**	**90%→35%**	**90%→CDI**	**90%→90%**	**CDI**	**CDI→CDI**	**90%→PPR[2]**
Season	**Cane mass per grapevine (kg)**									
2006/07	0.98 a	0.83 ab	0.76 bc	0.67 bc	0.78 bc	0.64 c	0.80 bc	0.77 bc	0.80 bc	0.75 bc
2007/08	1.17 a	0.85 bcd	0.86 bc	0.72 cde	0.88 b	0.71 de	0.79 bcde	0.69 e	0.75 bcde	0.87 b
2008/09	1.19 a	0.86 b	0.85 b	0.69 bc	0.77 bc	0.68 bc	0.76 bc	0.64 c	0.84 b	0.82 bc
Mean	*1.11 a*	*0.85 b*	*0.82 b*	*0.69 cd*	*0.81 b*	*0.68 d*	*0.78 bc*	*0.70 cd*	*0.80 b*	*0.81 b*
	Cane mass (t/ha)									
2006/07	3.2 a	2.7 ab	2.5 bc	2.2 bc	2.6 bc	2.1 c	2.6 bc	2.5 bc	2.6 bc	2.4 bc
2007/08	3.8 a	2.8 bcd	2.8 bc	2.4 cde	2.9 b	2.3 de	2.6 bcde	2.3 e	2.5 bcde	2.9 b
2008/09	3.9 a	2.8 b	2.8 b	2.3 bc	2.5 bc	2.2 bc	2.5 bc	2.1 c	2.8 b	2.7 bc
Mean	3.6 a	2.8 b	2.7 b	2.3 cd	2.7 b	2.2 d	2.6 bc	2.3 cd	2.6 b	2.7 b

[1] Continuous deficit irrigation where grapevines were irrigated frequently, but with low volumes of water to allow the soil to dry out gradually.
[2] Partial profile refill where the soil profile was only refilled partially during irrigations to maintain the plant available water between 40% and 60% depletion.
[3] Values designated by the same letter within each row do not differ significantly ($p \leq 0.05$).

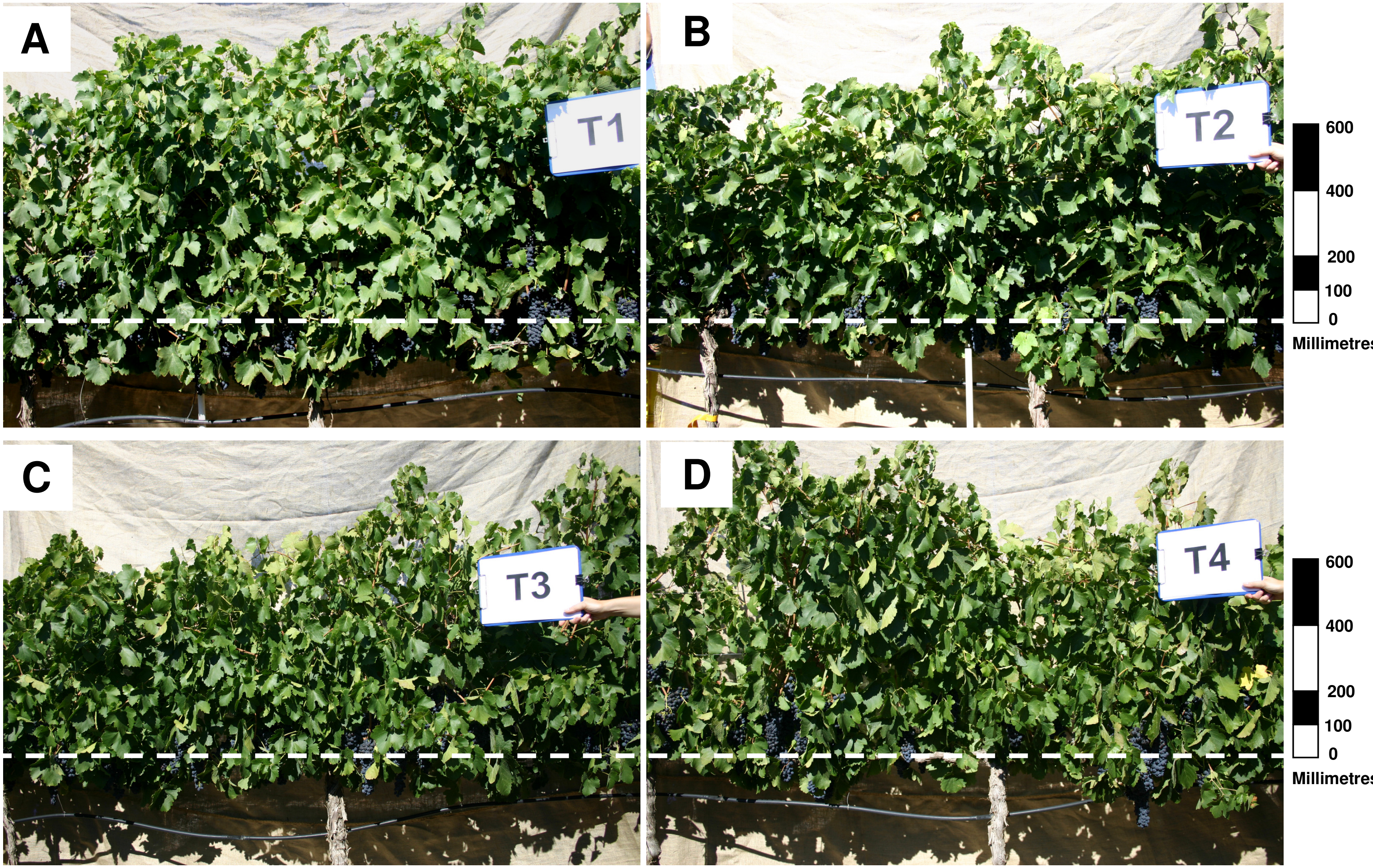

Figure 4.12 Examples of Shiraz/110R grapevines in a fine sandy loam soil that were irrigated (A) at 30% to 40% PAW depletion level (T1), (B) at 70% to 80% plant available water (PAW) depletion before véraison and followed by irrigation at 30% to 40% PAW depletion during ripening (T2), (C) at 70% to 80% plant available water (PAW) depletion before véraison and followed by a continuous deficit irrigation strategy during ripening (T3) and (D) irrigated at 70% to 80% PAW depletion level (T4) near Robertson during the 2008/09 season. Dashed lines indicate cordon height (750 mm).

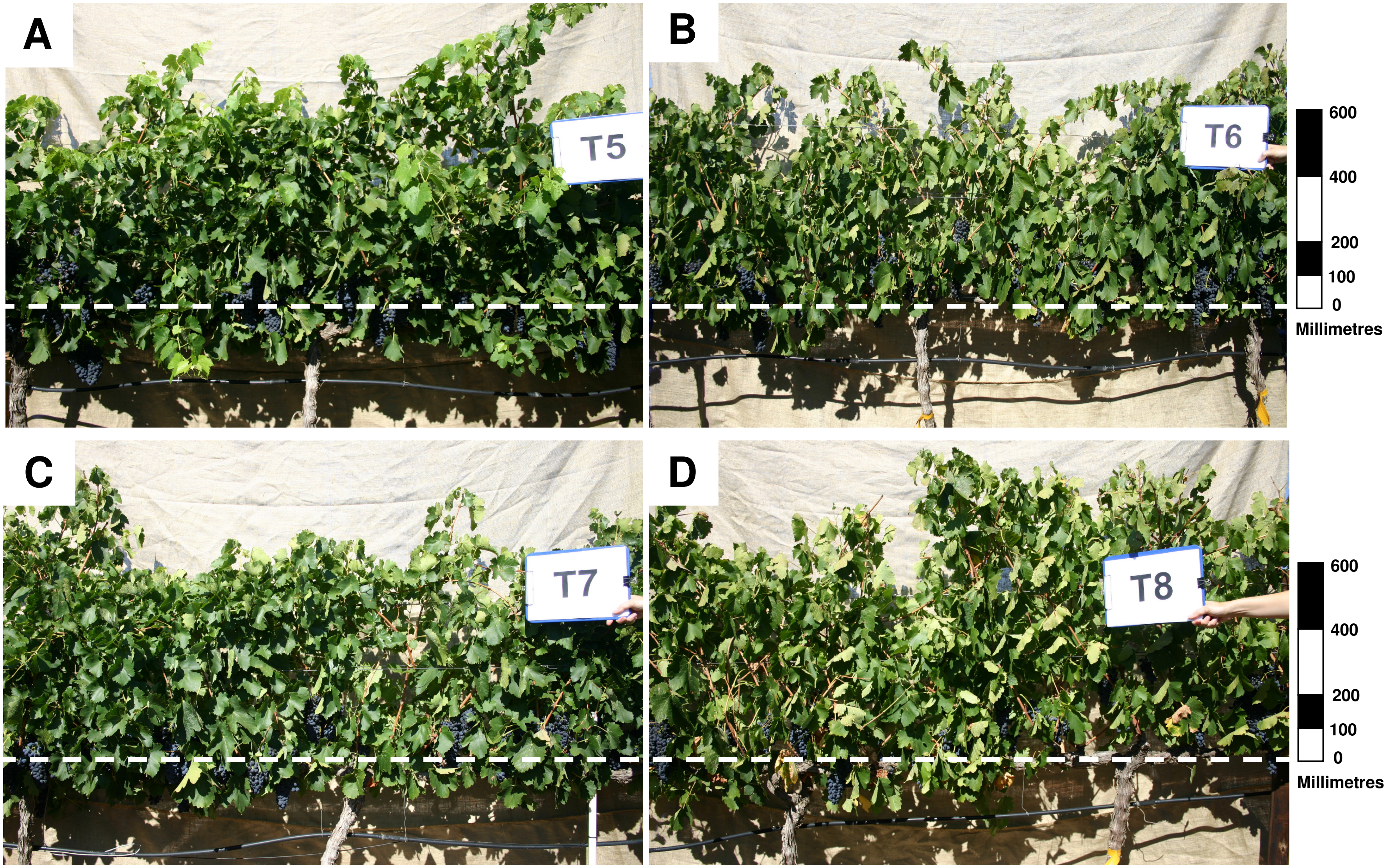

Figure 4.13 Examples of Shiraz/110R grapevines in a fine sandy loam soil that were irrigated (A) at *ca*. 90% plant available water (PAW) depletion before véraison and followed by irrigation at 30% to 40% PAW depletion during ripening (T5), (B) at *ca*. 90% plant available water (PAW) depletion before véraison and followed by a continuous deficit irrigation strategy during ripening (T6), (C) at *ca*. 90% PAW depletion level (T7) and (D) at a continuous deficit irrigation strategy (T8) near Robertson during the 2008/09 season. Dashed lines indicate cordon height (750 mm).

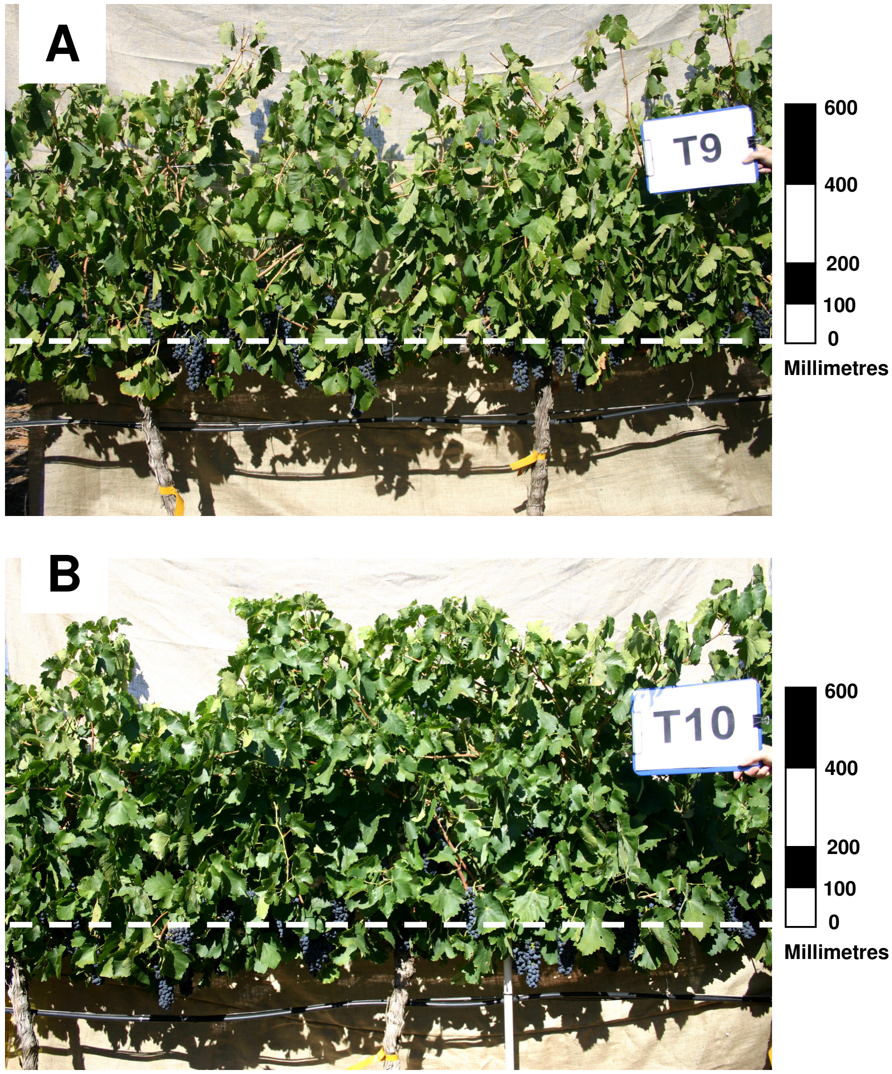

Figure 4.14 Examples of Shiraz/110R grapevines in a fine sandy loam soil that were irrigated (A) according to a continuous deficit irrigation strategy, which included the refilling of the profile at véraison (T9) and (B) at *ca*. 90% plant available water (PAW) depletion before véraison followed by a partial profile refill irrigation strategy during ripening (T10) near Robertson during the 2008/09 season. Dashed lines indicate cordon height (750 mm).

Figure 4.15 Examples of Shiraz/110R grapevines in a fine sandy loam soil that were irrigated at *ca*. 90% plant available water (PAW) depletion before véraison (A) and followed by irrigation at 30% to 40% PAW depletion during ripening (B), near Robertson from the 2006/07 to the 2008/09 season. Circles indicate shoot re-growth that occurred during ripening.

According to the norms for leaf analyses (Saayman, 1981) no nutrient deficiencies occurred in the 2006/07 and 2008/09 seasons (Table 4.7). Furthermore, leaf mineral contents did not show differences between irrigation strategies or trends with respect to irrigation volumes applied (data not shown). The only exception was higher leaf K content in the case of T1, T2 and T5 compared to the other irrigation strategies during the 2008/09 season. Higher soil water availability, in particularly during the ripening period, probably resulted in higher leaf K contents. Root absorbing efficiency and the amount of K absorbed by roots are determined by morphological root properties, root metabolism, photosynthetic rate of above ground organs, crop load and K demand of the shoots (Agenbach, 2006 and references therein). During ripening, the high level of available water of the T1, T2 and T5 strategies caused actively growing shoots and increased water use. The actively growing shoots probably had a high K demand, and since soil water was readily available, K in the soil solution would be more readily absorbed by roots compared to grapevines exposed to soil water constraints. This was confirmed by the increase in leaf K content with an increase in total seasonal precipitation, *i.e.* rainfall and irrigation (Figure 4.16).

4.3.4 Yield components

Berry mass decreased from véraison to harvest where grapevines were irrigated at 30% to 40% PAW depletion throughout the season during the 2006/07 and 2008/09 seasons (Figures 4.17 to 4.20). However, in the case of most of the deficit irrigation strategies berry mass increased from véraison to harvest. In the case of the CDI strategy (T8), which received relatively small irrigation amounts from mid-January (véraison) until early March (harvest), berry mass remained relatively constant. In the case of T1 grapevines, the decrease in berry mass can be explained by the double sigmoid growth curve of grape berries (Coombe, 1976; Deloire, 2010a). These berries were on the downward slant at the end of the growth curve since they took longer to reach the target sugar levels for harvest (Mehmel, 2010).

Water deficits, irrespective of the irrigation strategy, reduced berry size in comparison to the grapevines most frequently irrigated during ripening(T1 & T2) (Figures 4.17 to 4.20). The T5 grapevines produced smaller berries even though grapevines received the same irrigation volumes and at the same frequency as those of T1 and T2 during ripening. This suggested that the higher water constraints in

Table 4.7 The seasonal effect on the leaf blade nutrient content at harvest of Shiraz/110R in a fine sandy loam soil near Robertson during the 2006/07 and 2008/09 seasons.

	Leaf blade element										
	N	P	K	Ca	Mg	Na	Mn	Fe	Cu	Zn	B
Season	(%)					(mg/kg)					
2006/07	2.00±0.10	0.14±0.02	0.73±0.13	2.74±0.23	0.55±0.08	810±273	249±28	168±28	7±1	34±3	88±27
2008/09	1.96±0.11	0.11±0.02	0.35±0.10	1.81±0.17	0.40±0.04	444±175	123±19	152±31	3±1	39±3	60±17

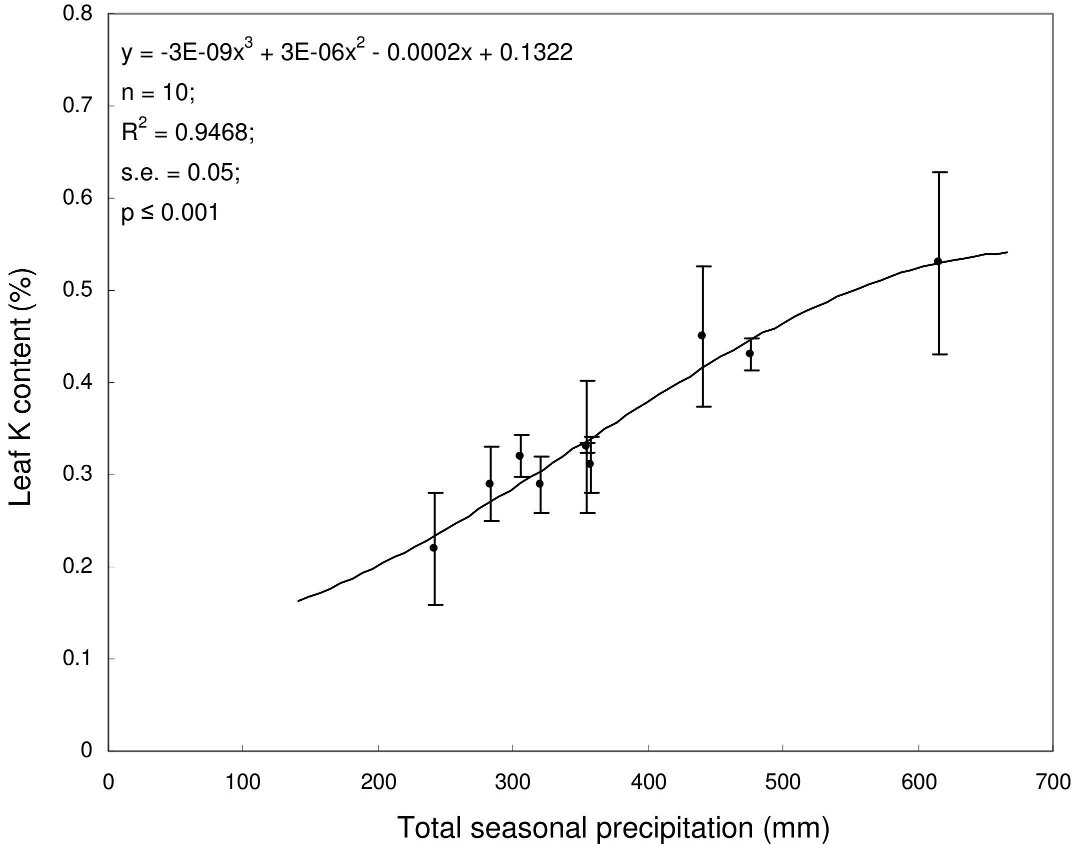

Figure 4.16 Relationship between total seasonal precipitation (rainfall and irrigation) and the mean leaf K content of Shiraz/110R grapevines and the soil water content of a fine sandy loam soil as measured before harvest in the 2008/09 season near Robertson. Vertical bars indicate standard deviation (n = 3).

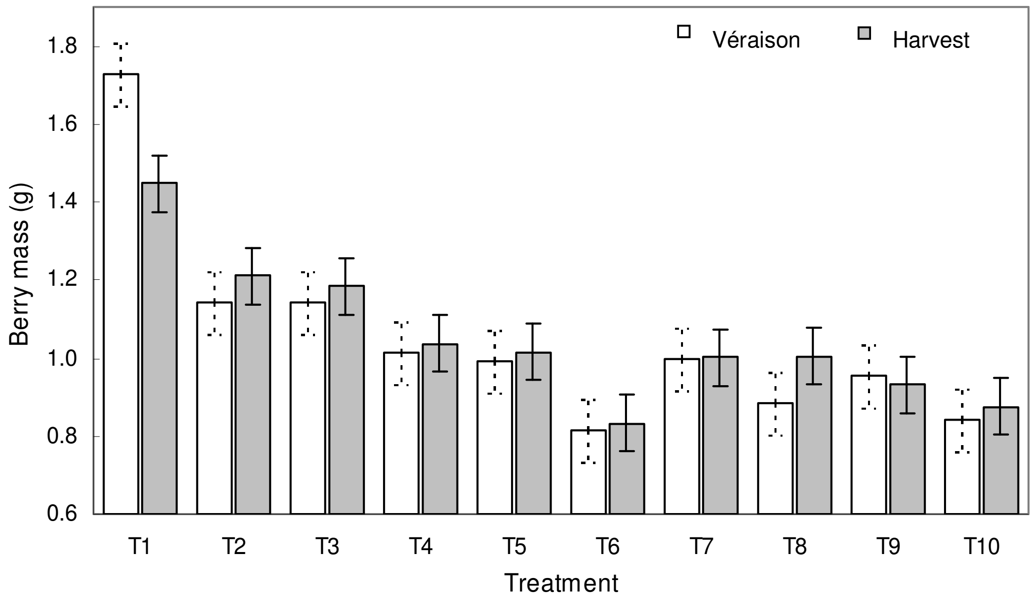

Figure 4.17 Effect of ten different irrigation strategies on the berry mass of Shiraz/110R in a fine sandy loam soil near Robertson at vérasion and harvest respectively in the 2006/07 season. Vertical bars indicate least significant difference per phenological phase at the 95% confidence interval.

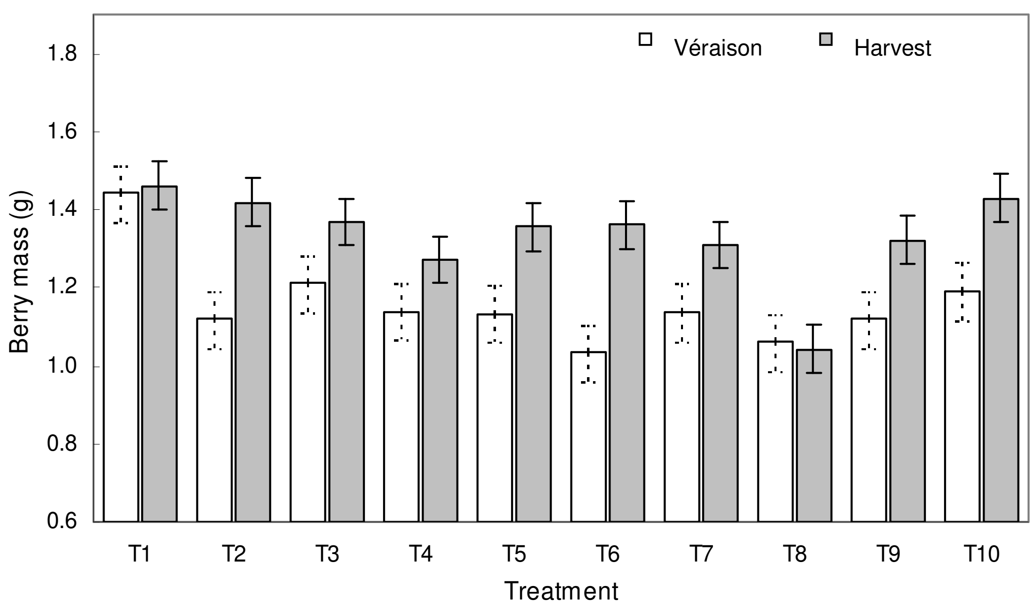

Figure 4.18 Effect of ten different irrigation strategies on the berry mass of Shiraz/110R in a fine sandy loam soil near Robertson at vérasion and harvest respectively in the 2007/08 season. Vertical bars indicate least significant difference per phenological phase at the 95% confidence interval.

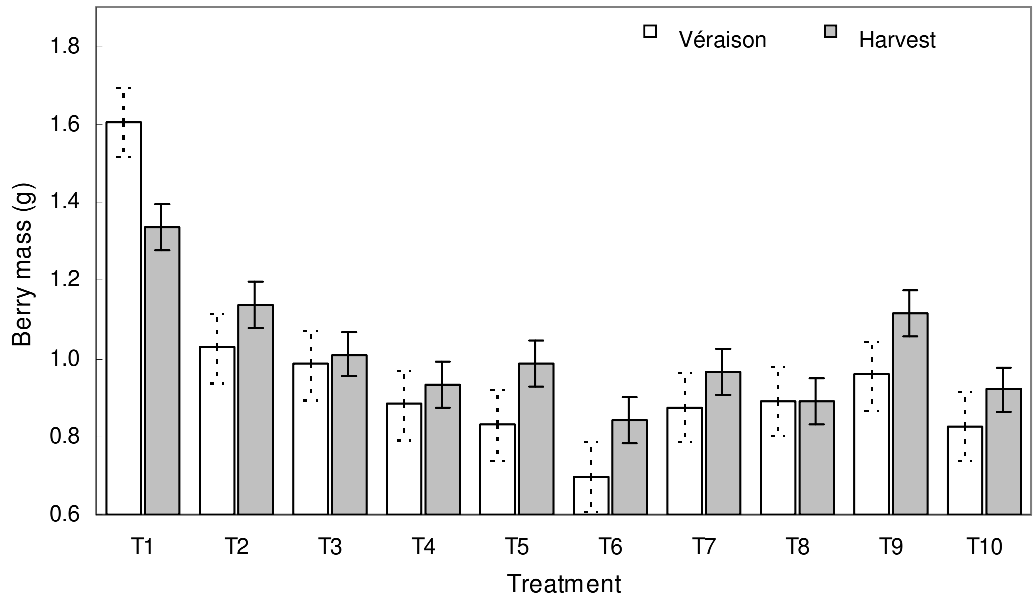

Figure 4.19 Effect of ten different irrigation strategies on the berry mass of Shiraz/110R in a fine sandy loam soil near Robertson at vérasion and harvest respectively in the 2008/09 season. Vertical bars indicate least significant difference per phenological phase at the 95% confidence interval.

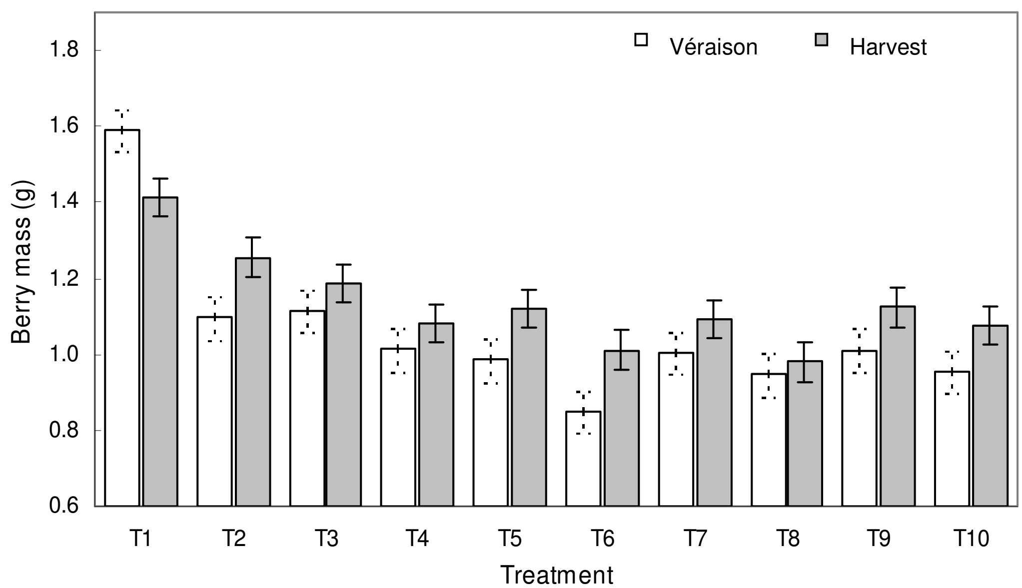

Figure 4.20 Effect of ten different irrigation strategies on the mean berry mass of Shiraz/110R in a fine sandy loam soil near Robertson at vérasion and harvest, respectively. Results are the mean for the 2006/07, 2007/08 & 2008/09 seasons and vertical bars indicate least significant difference per phenological phase at the 95% confidence interval.

the T5 grapevines compared to the T2 ones during the pre-véraison period probably limited berry enlargement, which resulted in smaller berries at harvest. These results confirm earlier findings that more frequent irrigations during ripening cannot reverse the smaller berry size caused by water deficits between flowering and pea size (Smart *et al*., 1974; Van Rooyen *et al*., 1980; McCarthy, 1997; Ojeda *et al*., 2002). On average, berry mass of Shiraz grapevines exposed to medium (T2) and strong (T5) levels of water deficit was 1.2 g and 1.0 g, respectively. The berry mass of grapevines that experienced strong levels of water deficit was similar to the Shiraz berry mass reported by Ojeda *et al.* (2002). Berries of grapevines exposed to medium deficit levels were 0.4 g/berry smaller than those reported by Ojeda *et al.* (2002). The higher berry mass measured during the 2007/08 season compared to the other two seasons was probably due to higher and more frequent rainfall, particularly during February 2008 (Table 3.4). With the exception of the T8 berries, mean berry mass in the current study was higher compared to the mean mass of 0.95 g per berry reported for Shiraz/99R in the Stellenbosch region (Ellis, 2008). The higher mean berry mass can be attributed to the 2007/08 season when berry mass was relatively high due to high rainfall during this season, particularly during ripening. During the 2006/07 and 2008/09 seasons, berry mass of grapevines irrigated at *ca*. 90% PAW depletion before véraison (T5, T6 & T7), *ca*. 70% to 80% PAW depletion throughout the season (T4) or with minimal irrigation during ripening (T8) was comparable to Shiraz berry sizes reported for the Stellenbosch region (Ellis, 2008).

The average crop load amounted to 43±7 bunches per grapevine over the three seasons in which the trial was conducted. Different irrigation volumes and water constraints do not have an effect on the number of bunches formed by grapevines, but does effect bunches size (Ashley, 2004). Lower yields of Merlot in the Coastal region of South Africa were related to smaller bunch mass (Myburgh, 2011a). Grapevines irrigated at high depletion levels during the pre-véraison period followed by the CDI or a high PAW depletion level strategy during ripening tended to produce the smallest bunches (Table 4.8).

Table 4.8 Effect of ten irrigation strategies on the yield components and the irrigation water productivity of Shiraz/110R in a fine sandy loam soil near Robertson during the 2006/07, 2007/08 and 2008/09 seasons.

	Treatment number									
	T1	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**	**T9**	**T10**
	Plant available water depletion pre-véraison → post-véraison									
	35%→35%	**75%→35%**	**75%→CDI[1]**	**75%→75%**	**90%→35%**	**90%→CDI**	**90%→90%**	**CDI**	**CDI→CDI**	**90%→PPR[2]**
Season	**Bunch mass (g)**									
2006/07	160 a[3]	134 b	131 b	105 cd	113 bc	81 d	122 bc	117 bc	111 bc	81 d
2007/08	199 ab	212 a	196 ab	192 abc	189 abcd	169 cd	165 d	139 e	177 bcd	179 bcd
2008/09	171 a	155 ab	110 d	125 cd	153 bcd	116 cd	130 bcd	123 cd	141 bc	132 bcd
Mean	*177 a*	*167 ab*	*145 cde*	*141 cde*	*152 bcd*	*138 de*	*146 bcde*	*139 de*	*160 abc*	*130 e*
	Yield per grapevine (kg)									
2006/07	7.82 a	6.43 ab	6.80 ab	4.91 cde	5.94 bc	3.93 e	5.89 bc	4.90 cde	5.57 bcd	4.13 de
2007/08	7.79 ab	8.88 a	7.30 bc	7.10 bcd	7.46 b	5.57 ef	6.10 de	4.69 f	6.18 cde	5.99 de
2008/09	7.79 a	7.88 a	5.45 cd	6.11 bcd	7.22 ab	5.19 cd	7.49 ab	5.10 d	6.69 abc	6.59 abcd
Mean	7.80 a	7.73 a	6.52 bc	6.04 bc	6.87 ab	4.89 d	6.49 bc	4.89 d	6.14 bc	5.57 cd
	Yield (t/ha)									
2006/07	25.7 a	21.8 b	20.6 bc	17.7 c	17.5 c	13.5 d	19.8 bc	19.2 bc	18.0 c	12.3 d
2007/08	25.6 b	29.1 a	23.9 b	22.6 bc	24.4 b	18.3 de	20.0 cd	14.9 e	20.3 cd	19.6 cd
2008/09	25.1 a	25.5 a	17.6 bcd	21.1 abcd	23.3 a	16.7 cd	22.0 ab	16.4 d	21.6 abc	21.3 abcd
Mean	*25.6 a*	*25.4 ab*	*21.4 c*	*19.8 cd*	*22.5 bc*	*16.0 e*	*21.3 c*	*16.0 e*	*20.1 cd*	*18.3 de*
	Irrigation water productivity (kg/m^3)									
2006/07	5.1 e	5.9 de	11.7 ab	8.1 cd	6.5 de	8.2 cd	13.7 a	11.7 ab	10.4 bc	9.5 bc
2007/08	6.8 f	10.1 e	13.5 d	17.4 b	10.4 e	14.7 cd	16.0 bcd	29.1 a	16.9 bc	10.6 e
2008/09	6.5 f	9.0 f	15.4 de	14.4 de	10.6 ef	20.9 bc	63.4 a	25.1 b	14.1 de	16.7 cd
Mean	*6.1 d*	*8.3 cd*	*13.5 c*	*13.3 cd*	*9.2 cd*	*14.6 c*	*31.0 a*	*22.0 b*	*13.8 c*	*12.2 cd*

(1) Continuous deficit irrigation where grapevines were irrigated frequently, but with low volumes of water to allow the soil to dry out gradually.
(2) Partial profile refill where the soil profile was only refilled partially during irrigations to maintain the plant available water between 40% and 60% depletion.
(3) Values designated by the same letter within each row do not differ significantly ($p \leq 0.05$).

Grapevines that were irrigated at *ca*. 90% PAW depletion before véraison, and to a lesser extent those irrigated at 70% to 80% PAW depletion, produced less compact bunches (Figure 4.21). Similarly, an irrigation during flowering improved fruit set and increased berry size of Chenin blanc grapevines compared to non-irrigated ones that produced looser bunches with smaller berries (Van Zyl & Weber, 1977). Yield increased linearly as the bunch mass increased. The bunch mass of grapevines that were exposed the severe soil water constraints, *i.e.* irrigated only once SWC reached *ca*. 90% PAW depletion, and a CDI strategy before véraison, produced bunches much smaller than the 195 g per bunch of Shiraz/99R reported for the Stellenbosch region (Ellis, 2008).

During the 2007/08 season, more grey rot occurred in bunches of grapevines that were irrigated more frequently during ripening (Table 4.9). The higher mean relative humidity during the ripening phase in this particular season compared to the other two seasons (Table 3.3) could have contributed to the higher incidence of this disease.

Grapevine yield decreased with a decrease in irrigation volumes. Irrigation at 30% to 40% PAW depletion during ripening (T1, T2 & T5) produced the highest yields compared to less frequently irrigated ones (Table 4.8). Grapevines that were irrigated according to the CDI strategies during ripening tended to produce the lowest yields. These trends were consistent over the three seasons. Yields produced by all the strategies were higher than the 11.9 ton/ha mean yield for Shiraz in the Robertson region as calculated using data obtained from South African Wine Industry Information & Systems data base (Anonymous, 2010).

Irrigation at *ca.* 90% PAW depletion throughout the season (T7) increased the IWP, *i.e.* mass grapes produced per unit irrigation water applied, substantially compared to the rest of the irrigation strategies (Table 4.8). It was evident that more frequent irrigations, particularly during ripening, resulted in lower IWP.

Where grapevines were irrigated according to the CDI strategy without a refill at véraison (T8), low yields caused the lower IWP compared to T7. Shiraz grapevines in Australia irrigated at 100% and 70% of reference evapotranspiration (ET_o), had a mean irrigation water use index (IWUI) of 3.2 t/ML or kg/m^3 (Stevens *et al*., 2010).

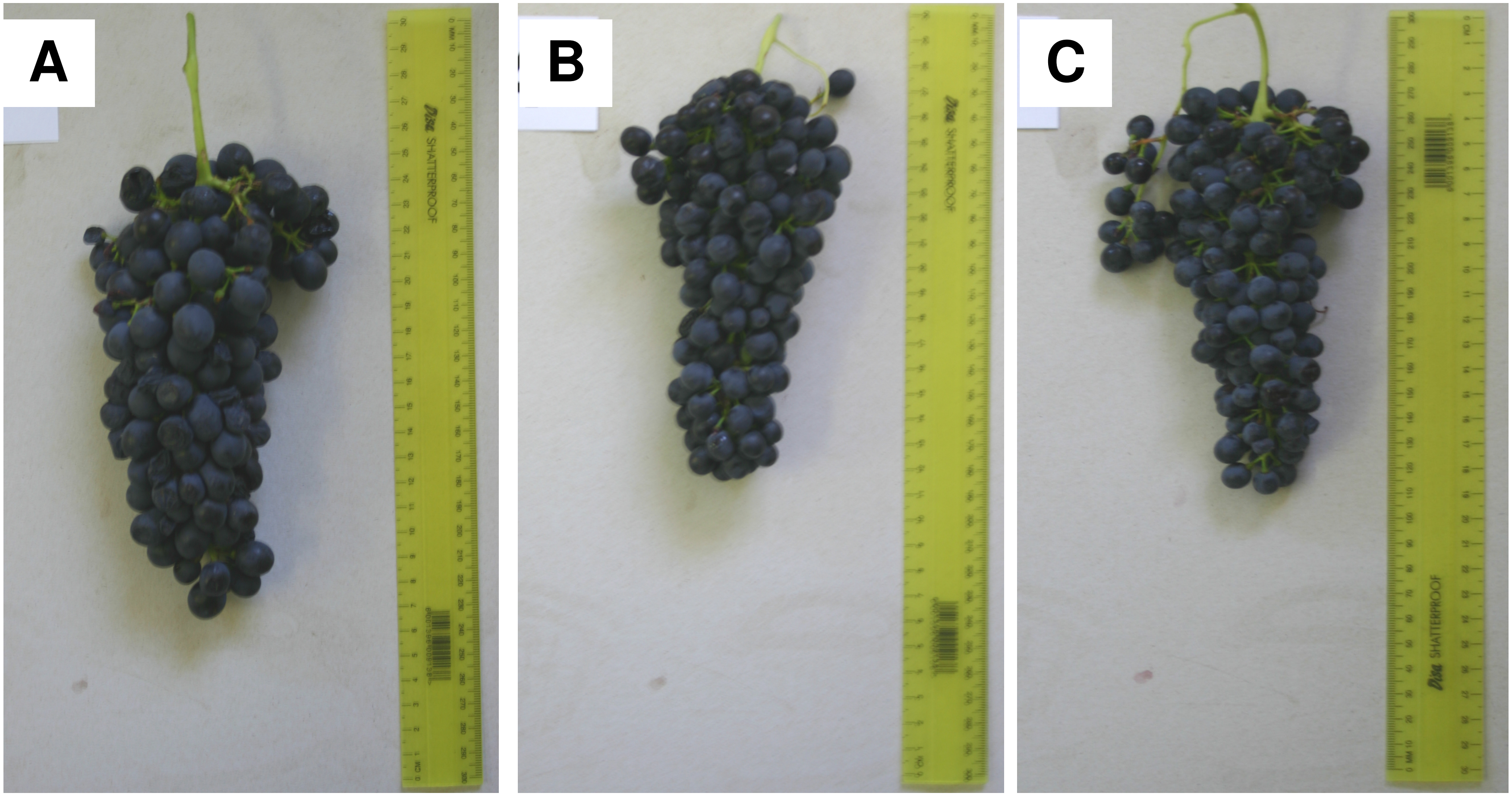

Figure 4.21 Example of the bunches of Shiraz/110R grapevines in a fine sandy loam soil that were (A) irrigated at 30% to 40% PAW depletion level (T1), (B) irrigated at 70% to 80% PAW depletion level (T4) and (C) irrigated at *ca.* 90% PAW depletion level (T4) near Robertson from the 2006/07 to the 2008/09 season.

Table 4.9 Effect of ten irrigation strategies on the percentage of Shiraz/110R bunches effected by grey rot (*Botrytis cinerea*) near Robertson during the 2007/08 season.

	Treatment number									
	T1	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**	**T9**	**T10**
	Plant available water depletion pre-véraison → post-véraison									
	35%→35%	**75%→35%**	**75%→CDI[1]**	**75%→75%**	**90%→35%**	**90%→CDI**	**90%→90%**	**CDI**	**CDI→CDI**	**90%→PPR[2]**
	Percentage of bunches effected by grey rot (%)									
2007/08	57 a[3]	41 ab	28 bcd	21 cde	33 bc	12 def	17 cdef	0 f	5 ef	27 bcd

[1] Continuous deficit irrigation where grapevines were irrigated frequently, but with low volumes of water to allow the soil to dry out gradually.
[2] Partial profile refill where the soil profile was only refilled partially during irrigations to maintain the plant available water between 40% and 60% depletion.
[3] Values designated by the same letter within each row do not differ significantly ($p \leq 0.05$).

This is substantially lower than the IWP of T1 grapevines in this study. The low value suggests that the grapevines in the Australian study were probably over-irrigated. Furthermore, the lack of differences between the treatments in the latter study emphasizes the danger of irrigation research done by applying irrigation by means of a percentage of ET_o. Furthermore, the use of water saving technology such as drip irrigation, in combination with regular soil based measurements to ensure proper irrigation management, can be used to save water without negative effects on yield.

4.3.5 Juice characteristics

Grapes of the T7 and T8 strategies reached the target TSS content of 24˚B earlier than the other strategies (Table 4.10). The other irrigation strategies delayed TTS accumulation by approximately one week, or two weeks in the case of the T1 and T2 strategies. It was previously shown that excessive water availability or canopies that are actively growing during stage III of berry development (ripening) will delay berry ripening, while controlled water deficits and well exposed canopies will enhance TTS accumulation and berry ripening (Jackson & Lombard, 1993). Due to logistical problems, particularly during the 2006/07 season, the juice TTS of some of the strategies were higher than the target 24˚B when the grapes were harvested (Table 4.10).

The mean TTA in the juice of grapevines irrigated with the CDI strategy throughout the season (T8) was higher compared to the other treatments, particularly that of grapevines that were most frequently irrigated during ripening (Table 4.10). Since pH is a measurement of “active” acidity, pH will increase with a decrease in acidity (Bruwer, 2010; Myburgh, 2011d). The juice pH of T8 was also significantly lower compared to the rest of the treatments (Table 4.10). This can be explained by the fact that the berries of T8 had the same concentration acidity per berry as those of T1, but since T1 berries were bigger they had a lower juice TTA concentration than the T8 juice (data not shown). For the rest of the strategies, the TTA concentrations per berry were comparable to that of the T8 berries (data not shown).

Juice cation concentrations were within the norms for wine grapes (Saayman, 1981; Ough & Kriel, 1985; Haight & Gump, 1995; Myburgh, 2006b). The cation contents in the juice were not affected by the different irrigation strategies or the irrigation

Table 4.10 Effect of ten irrigation strategies on the total dissolved solids, total titratable acidity and pH of grape juice of Shiraz/110R grapevines in a fine sandy loam soil near Robertson during the 2006/07, 2007/08 and 2008/09 seasons.

	Treatment number									
	T1	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**	**T9**	**T10**
	Plant available water depletion pre-véraison → post-véraison									
	35%→35%	**75%→35%**	**75%→CDI[1]**	**75%→75%**	**90%→35%**	**90%→CDI**	**90%→90%**	**CDI**	**CDI→CDI**	**90%→PPR[2]**
Season	**Total dissolved solids (°B)**									
2006/07	24.4 de[3]	24.3 de	23.8 e	25.0 cd	24.8 cd	26.2 ab	26.6 a	25.9 ab	25.5 bc	25.4 bc
2007/08	24.2 abc	23.2 c	24.2 abc	23.6 bc	23.9 bc	23.6 bc	24.5 ab	25.3 a	24.0 bc	23.5 bc
2008/09	25.0 a	24.2 ab	24.3 ab	24.8 ab	25.1 a	24.8 ab	24.9 ab	24.9 ab	24.5 ab	23.9 b
Mean	*24.5 bcd*	*23.9 d*	*24.1 cd*	*24.5 bcd*	*24.6 bc*	*24.9 ab*	*25.3 a*	*25.4 a*	*24.7 bc*	*24.3 bcd*
	Total titratable acidity (g/L)									
2006/07	4.4 e	4.5 de	4.8 bc	5.0 abc	5.1 a	4.7 cd	4.9 abc	5.0 abc	4.9 abc	5.0 ab
2007/08	5.8 b	5.2 d	5.1 d	5.6 bc	5.3 cd	5.5 bcd	5.5 bcd	6.5 a	5.4 bcd	5.1 d
2008/09	5.3 cd	5.3 cd	5.6 c	6.4 b	4.5 e	5.6 c	5.0 cde	7.1 a	4.9 de	5.4 cd
Mean	*5.2 c*	*5.0 c*	*5.2 c*	*5.7 b*	*5.0 c*	*5.3 bc*	*5.1 c*	*6.2 a*	*5.1 c*	*5.2 c*
	pH									
2006/07	3.81 a	3.81 a	3.65 cde	3.74 ab	3.58 e	3.70 bcd	3.71 bc	3.62 de	3.65 bcde	3.59 e
2007/08	3.92 a	3.87 ab	3.90 a	3.85 ab	3.93 a	3.81 b	3.90 a	3.68 c	3.81 b	3.90 a
2008/09	3.78 a	3.53 cd	3.68 ab	3.54 cd	3.60 bd	3.46 d	3.47 d	3.35 e	3.60 bc	3.46 de
Mean	*3.84 a*	*3.74 b*	*3.74 b*	*3.71 bc*	*3.70 bc*	*3.66 c*	*3.69 bc*	*3.55 d*	*3.69 bc*	*3.65 c*

(1) Continuous deficit irrigation where grapevines were irrigated frequently, but with low volumes of water to allow the soil to dry out gradually.
(2) Partial profile refill where the soil profile was only refilled partially during irrigations to maintain the plant available water between 40% and 60% depletion.
(3) Values designated by the same letter within each row do not differ significantly ($p \leq 0.05$).

volumes applied (data not shown). There seemed, however, to have been a vintage effect between the mean cation concentrations (Table 4.11).

4.3.6 Wine quality characteristics

High pre- and post-véraison soil water deficits (T6, T7 and T8) improved wine colour substantially compared to grapevines that were frequently irrigated through the season (T1) and in the post-véraison period (T2 and T5) (Table 4.12). Shiraz grapevines exposed to strong water constraints during ripening produced higher anthocyanins per gram of berry skin compared to that of grapevines that received adequate irrigation (Ojeda *et al.*, 2002). Irrigation strategies which induced higher plant water constraints (T6, T7 and T8) had a positive effect on the wine berry and spicy characters, compared to strategies that where irrigations were applied more frequently. The nutty and smoky characters in wines showed a similar trend, but to a lesser extent (data not shown). Shiraz grapevines in Australia that received half of 1.0 ML/ha the irrigation applied to the control treatment produced wines with a more prominent spicy (liquorice) character (Ristic *et al.*, 2010). Shiraz grapevines in the Stellenbosch area that were exposed to strong water deficits during the pre-véraison period and that received an irrigation a month after véraison, produced lower grape phenolics compared to non-irrigated grapevines and ones that only received an irrigation at véraison (Ellis, 2008). Lower grape phenolic compound concentrations were also found at grapevines that received frequent irrigations throughout the season (Ellis, 2008).

Grapevines irrigated at 30% to 40% PAW depletion during ripening (T1, T2 & T5) produced the poorest overall sensorial wine quality (Table 4.12) This trend was also observed where Pinotage was irrigated at high frequencies in the Breede River Valley region (Myburgh, 2011d). Although grapevines of the T5 strategy were irrigated at the same frequency as those of T1 and T2 during ripening, wine colour, berry and spicy characters, as well as overall quality of T5 wines tended to be higher compared to T1 and T2. This can probably be attributed to the higher water constraints that the T5 grapevines were exposed to during the pre-véraison period compared to those of T1 and T2. Better overall wine quality was obtained where grapevines were irrigated at high PAW

Table 4.11 The mean juice cation content of Shiraz/110R in a fine sandy loam soil near Robertson for the 2006/07, 2007/08 and 2008/09 seasons.

Season	Na	Mg	Ca	K	P	N
	(mg/L)					
2006/07	44.98 a[1]	177.84 a	69.69 ab	1704.97 a	130.09 a	172.13 a
2007/08	17.94 c	165.07 a	76.96 a	1900.14 a	123.75 a	171.73 a
2008/09	29.44 b	120.70 b	66.24 b	1261.41 b	98.88 b	164.52 a

[1] Values designated by the same letter within each column do not differ significantly ($p \leq 0.05$).

Table 4.12 The effect of ten irrigation strategies on the sensorial wine components of Shiraz/110R in a fine sandy loam soil near Robertson during the 2006/07, 2007/08 and 2008/09 seasons.

	Treatment number									
	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
	Plant available water depletion pre-véraison → post-véraison									
	35%→35%	75%→35%	75%→CDI[1]	75%→75%	90%→35%	90%→CDI	90%→90%	CDI	CDI→CDI	90%→PPR[2]
Season	Colour (%)									
2006/07	44.6 d[3]	57.7 cd	59.9 c	77.4 ab	64.4 bc	79.0 a	79.2 a	74.7 ab	64.7 bc	70.9 abc
2007/08	33.5 de	17.2 e	40.4 cd	50.7 bc	45.5 bcd	59.7 b	61.3 b	82.6 a	49.9 bcd	49.5 bcd
2008/09	37.8 ab	28.4 b	35.5 ab	39.4 ab	35.5 ab	44.9 ab	54.3 a	[4]	48.2 ab	28.0 b
Mean	*38.6 fg*	*34.4 g*	*45.3 ef*	*55.9 bcd*	*48.5 def*	*61.1 abc*	*65.0 ab*	*72.4 a*	*54.2 cde*	*52.7 cde*
	Berry character (%)									
2006/07	39.8 d	42.1 cd	48.8 abcd	56.3 a	53.5 abc	55.6 ab	57.8 a	50.1 abcd	44.3 bcd	51.5 abcd
2007/08	43.9 ef	39.1 f	47.3 cde	53.8 bc	48.6 cde	52.7 bcd	58.5 ab	62.6 a	45.2 def	45.4 def
2008/09	42.2 abc	41.9 abc	39.7 bc	41.1 abc	43.1 abc	45.7 ab	49.8 a	[4]	47.3 ab	33.9 c
Mean	*42.0 d*	*41.0 d*	*45.3 cd*	*50.4 abc*	*48.4 bc*	*51.4 ab*	*55.4 a*	*54.7 a*	*45.6 cd*	*45.7 bcd*
	Spicy character (%)									
2006/07	32.2 d	36.0 cd	32.5 d	50.0 a	42.5 b	41.8 bc	44.6 ab	43.7 ab	38.9 bc	41.5 bc
2007/08	36.6 cd	27.2 e	42.8 b	44.6 b	36.1 d	45.8 ab	51.1 a	51.1 a	42.4 bc	41.3 bcd
2008/09	41.3 abc	35.7 bc	38.6 abc	42.6 ab	38.5 abc	39.7 abc	46.2 a	[4]	39.8 abc	32.2 c
Mean	*36.7 de*	*33.0 e*	*38.0 cd*	*45.8 ab*	*39.0 cd*	*42.2 bc*	*47.3 a*	*47.1 ab*	*40.4 cd*	*40.0 cd*
	Overall wine quality (%)									
2006/07	41.6 e	44.8 de	46.2 cde	60.6 a	52.9 abcd	58.3 a	60.3 a	57.2 ab	48.2 bcde	55.1 abc
2007/08	35.9 f	23.0 g	40.2 def	46.2 cd	36.3 ef	49.2 bc	56.9 b	65.8 a	43.6 cd	42.9 cde
2008/09	43.1 ab	36.8 b	42.7 ab	44.2 ab	37.9 b	41.7 ab	52.6 a	[4]	44.2 ab	36.8 b
Mean	*40.2 de*	*34.3 e*	*42.4 d*	*50.4 bc*	*42.3 d*	*49.5 c*	*56.6 ab*	*59.4 a*	*45.4 cd*	*45.8 cd*

[1] Continuous deficit irrigation where grapevines were irrigated frequently, but with low volumes of water to allow the soil to dry out gradually.
[2] Partial profile refill where the soil profile was only refilled partially during irrigations to maintain the plant available water between 40% and 60% depletion.
[3] Values designated by the same letter within each row do not differ significantly ($p \leq 0.05$).
[4] During the 2008/09 wines of two replications of T8 were faulty. Consequently, wines of this treatment were excluded from the statistical analyses.

depletion levels and exposed to high water constraints during ripening (T4, T7 & T8). Müller-Thurgau grapevines, grown in pots with dry soil conditions during ripening produced wine which was rated as “fruity, fragrant and elegant”, while grapevines exposed to adequate water availability during this period produced wines rated as “full-bodied and less elegant” (Becker & Zimmerman, 1983).

The combined effects of wine colour and spicy character explained *ca.* 91% of the variation in overall sensorial wine quality by means of multiple linear regression in the following equation:

$$Q_w = 4.54 + 0.42^*C_w + 0.49^*S_w \quad (R^2 = 0.9130;\ se = 3.1;\ p < 0.001) \qquad (4.1)$$

where Q_w is overall sensorial wine quality, C_w is sensorial wine colour and S_w is sensorial wine spicy character. Actual overall sensorial wine quality was closely related to the predicted quality over the three seasons (Figure 4.22).

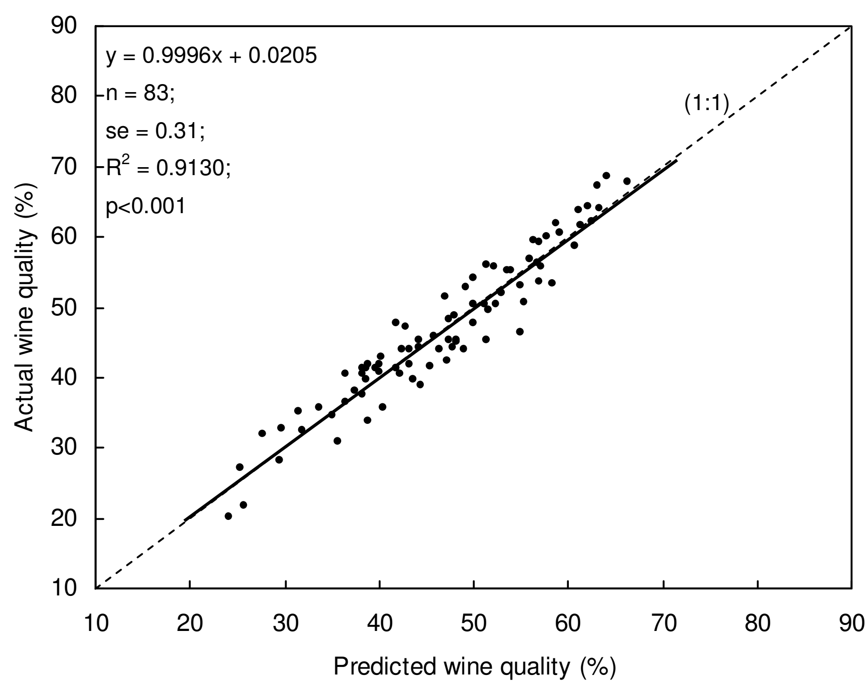

Figure 4.22 Relationship between actual sensorial wine quality and predicted wine quality of Shiraz wines during the 2006/07, 2007/08 and 2008/09 seasons near Robertson. The dashed line indicates the 1:1 ratio between the actual and predicted overall wine quality.

3.6. CONCLUSIONS

Under the given conditions, the different irrigation strategies did not have any effect on root distribution and density. The drip irrigation system and wetting depth during establishment of the vineyard seemed to have played a dominant role in the characteristics of the root systems. Water constraints in Shiraz grapevines were increased by allowing higher soil water depletion before irrigations were applied compared to constraints in more frequently irrigated grapevines. Shoot growth of grapevines exposed to high to severe water deficits in the pre-véraison period stopped before mid December. Shoots of grapevines that were exposed to high or severe water deficits before véraison followed by more frequent irrigation during ripening showed active shoot growth.

High frequency irrigation strategies during ripening can delay sugar accumulation due to dilution of sugar in the larger berries. Except for the wettest strategy, and where grapevines were subjected to the CDI strategy throughout the season, berry mass increased during ripening, *i.e.* from véraison to harvest. Water deficits had a negative effect on berry mass, bunch size and yield. Irrigation strategies where soil water higher depletion levels were allowed had a positive effect on the IWP of grapevines compared to the frequently irrigated or CDI strategies.

Higher water constraints in grapevines, particularly during ripening, improved sensorial wine colour and enhanced the more prominent wine aromas. Grapevines that were irrigated at a high frequency during ripening produced wines with diluted character flavours and aromas and inferior overall quality. Under the given conditions, wine colour and spicy character were the dominant factors in determining overall sensorial wine quality.

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Chapter 5

GENERAL CONCLUSIONS AND RECOMMENDATIONS

CHAPTER 5
GENERAL CONCLUSIONS AND RECOMMENDATIONS

5.1. GENERAL CONCLUSSIONS

Drip-irrigated grapevines needed two to four times less water compared to grapevines irrigated by means of full surface micro-sprinkler irrigation at similar depletion levels, namely 50% and 75% plant available water (PAW) depletion. Monthly and seasonal crop evapotraspiration (ET_c) values of drip-irrigated grapevines were almost half of full surface micro-sprinkler irrigation under the same climatic conditions, most probably due to the lower evaporation losses from the soil surface. In areas that have lower relative humidity, higher ET_c losses might occur if irrigations are applied at similar PAW depletion levels as in this trial.

Grapevines irrigated frequently at low PAW depletion levels before véraison will have to be irrigated at a 25% higher crop coefficient (K_c) during ripening than grapevines irrigated at high soil water depletion levels before véraison followed by frequent irrigations at low PAW depletion levels after véraison. For strategies where irrigations were applied at high PAW depletion levels throughout the season, *i.e. ca.* 75% and *ca.* 90% PAW depletion, K_c values were 50% and 25%, respectively, of the K_c for *ca.* 35% PAW depletion. Crop coefficients of full surface irrigated grapevines in the same region, can be expected to be two to three times higher than the crop coefficients for drip irrigation determined in this study.

Different drip irrigation strategies should not have a significant effect on the grapevine root densities if the root system and structure developed properly during the establishment of the vineyard. Higher PAW depletion levels will have more negative plant water potentials as a result. Pre-véraison water constraints will cause lower shoot growth rates and no actively growing shoots will occur if water constraints are maintained during berry ripening. However, if pre-véraison water constraints are followed by a luxurious water supply during ripening shoot re-growth can be expected. The latter will compete with grape berries for photosynthetic products.

Water constraints had a negative effect on berry mass, bunch mass and yield of grapevines. However, the mass of grapes produced per unit volume of water was higher where grapevines experienced water constraints. Irrigations at high frequencies during ripening delayed sugar accumulation in the juice. In contrast to this, no irrigations or low irrigation volumes during ripening enhanced sugar accumulation to such an extent that the target level for harvest (24°B) was reached one to two weeks earlier compared to the frequently irrigated grapevines.

Grapevines that received frequent irrigation, *i.e.* at low PAW depletion levels, during ripening produced poorest overall wine quality. In contrast, high PAW depletion levels resulted in wines with the most prominent wine cultivar characters and the best wine colour and overall wine quality. The sensorial overall wine quality of the Shiraz wines was predominantly a function of sensorial wine colour and spicy character.

5.2. RECOMMENDATIONS

5.2.1. Recommendations for managing drip-irrigated vineyards in the Breede River Valley region

- When drip-irrigated vineyards are established, it is essential to wet the deeper soil layers. This will ensure sufficient vertical root distribution since roots will only develop in the presence of water. Deeper root systems will create a bigger root surface exposure to soil volume and the grapevines will better buffered if excessive drying of the soil accidentally occurs.
- When using the Penman-Monteith reference evapotranspiration to estimate ET_c for drip irrigation at *ca*. 35%, *ca*. 75% or *ca*. 90% PAW depletion throughout the season, K_c values of 0.4, 0.2 and 0.1, respectively, should be used.
- If grapevines need to be irrigated at a high PAW depletion level before véraison followed by *ca*. 35% PAW depletion during ripening, K_c values of 0.3 should be used for the post-véraison period.
- When the timing of irrigations are based on pressure bomb measurements, irrigations applied at stem water potentials of -0.9 MPa will result in the highest grapevine yields and poorest wine quality. The opposite yield and quality responses will be obtained when irrigations are applied when stem water potential reach -1.9 MPa.

- High yields can be obtained with less water by applying irrigations at 70% to 80% PAW depletion before véraison followed by 30% to 40% PAW depletion during ripening. When the Penman-Monteith reference evapotranspiration is used, K_c values of 0.2 before véraison and 0.3 during ripening should be used. This strategy can be followed if growers are not compensated for producing low grape yields of high quality, and are forced to produce high yields.
- If the objective of a Shiraz vineyard is top quality wine, grapevines should be irrigated at *ca*. 90% PAW depletion throughout the season (K_c = 0.1) or by means of a continuous deficit irrigation strategy until véraison (K_c = 0.25) and minimal irrigation volumes during ripening (K_c = 0.1).

5.2.2. Recommendations for future research

- Previous South African grapevine irrigation research has generally focussed on a single aspect of grapevine management, *i.e.* either manipulating the grapevine canopy, while all treatments received the same irrigation, or by the manipulation of soil water content, with the same canopy management were applied to all treatments. The combined effect of irrigation strategies and canopy management inputs needs to be investigated to determine if water constraints can be used to reduce canopy management inputs.
- The combined effect of real time atmospheric variables and soil water availability on grapevine water status needs to be determined. This will allow indirect real time plant based irrigation scheduling if atmospheric and soil conditions are monitored by means of automatic weather stations and reliable continuous logging soil water sensors, respectively.
- The effect of extreme water constraint conditions on the sugar accumulation and photosynthetic functioning of grapevines need to be investigated and compared to that of grapevines grown under luxurious conditions.
- The cumulative effect of water constraints over the season, or during berry ripening, needs to be related to wine quality aspects.
- The effect of different irrigation strategies and level of water constraints on the Rotundone (a bicyclic sesquiterpene – $C_{15}H_{22}O$) concentrations in the Shiraz grapes and wine should be investigated. This knowledge can be useful for the chemical assessment of Shiraz wine quality.

- The creation of a modelling tool for the wine industry to predict plant water potentials using the reigning climatic data and soil properties and water contents.